Coupling Life Cycle Assessment and Socioeconomic Scenarios for Climate Change Adaptation of the Energy-Water Nexus

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Dedication

This work is dedicated to my mother, Rabeeya Absar, who instilled in me the gumption to pursue my dreams, the wanderlust to travel the world and the curiosity to gain knowledge to my heart’s content!

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Abstract

The interdependency of water and energy resources is known as energy-water-nexus (EWN). Water is necessary for energy production and energy is integral to water acquisition and distribution. The carbon emissions associated with both water and energy sectors drive climate change. Climate change in return poses increasing stress on the energy water nexus and makes tradeoffs between resources necessary and increasingly challenging, given the constraints and uncertainty around resources. This dissertation focuses on the tradeoffs between greenhouse gas mitigation and water conservation in the energy-water-nexus and how adaptation policy can influence these tradeoffs.

To quantitatively understand these tradeoffs especially under future development pathways, a modeling framework is developed to first develop socioeconomic storylines that contain local information around energy water nexus, and a life cycle assessment model that quantifies the energy and water footprints for an energy system based on input data assessing various policy and technology pathways. In this dissertation, such a framework is developed and tested and applied in the context of shale gas production in Barnett Texas.

Three collaborative research manuscripts developed for this dissertation are presented as three chapters following an Introduction and summed up with a Conclusion. Chapter 1 develops sub-national and sectoral extensions of the global shared socioeconomic pathways (SSPs), as nested qualitative storylines, in order to identify future socioeconomic challenges for adaptation for the United States on national, regional and local scales. Chapter 2 develops a life-cycle assessment (LCA) model to evaluate the global warming potential and water scarcity footprints associated with multiple wastewater management options associated with shale gas production in the Barnett Shale play of Texas. Chapters 3 combines the two frameworks developed in Chapters 1 and 2, by testing the nested SSPs for Texas, by developing shared policy assumptions and quantifying them as input parameters to the LCA model, to evaluate energy and technology pathways around adaptation of hydraulic fracturing and water use in Texas. The Conclusion synthesizes the main findings from the three chapters and discusses opportunities to use the research to improve future policy decisions related to climate change and energy-water nexus.

Preface

“Those who contemplate the beauty of the earth find reserves of strength that will endure as long as life lasts. There is something infinitely healing in the repeated refrains of nature -- the assurance that dawn comes after night, and spring after winter.”
— **Rachel Carson**, **Silent Spring**

“Climate change is destroying our path to sustainability. Ours is a world of looming challenges and increasingly limited resources. Sustainable development offers the best chance to adjust our course.”
— **Ban Ki-moon**

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Introduction

The interdependency of water and energy resources is known as energy-water-nexus (EWN). Energy and water are indispensable inputs to any economy. We use water for electricity production directly through hydroelectric power generation and indirectly as a coolant for thermoelectric power plants and to extract fuels for energy use. We also use water to grow biofuels. Similarly, we use energy for water. A significant amount of electricity is used to withdraw, treat and transport water supplies and to treat wastewater. This coupling of energy and water resources is unique to every energy and water production and use technology. A constraint in one sector can lead to a constraint in the other. Failure to consider the interdependencies of energy and water sectors introduces vulnerabilities for instance; climate change introduces uncertainties in water resource availability and predictability. These may lead to constraints in the energy sector. Similarly, grid outages or other failures in the energy system can become constraints in the water and wastewater treatment sectors (Stillwell et al, 2011; Scanlon et al., 2013; DOE, 2014).

The carbon emissions associated with production, consumption and waste generated by both water and energy sectors drive climate change. Climate change in return poses increasing stress on the energy water nexus through increased frequency in drought, heat waves and uncertain water availability (Roy et al., 2012; Scanlon et al., 2013). Population growth and rise in temperatures, drive up the demand for energy and water resources, which may present significant additional shocks to the existing energy and water supply systems especially in the water stressed regions of the country given that there are other competing users of water such as agriculture, industry and households (Vörösmarty et al., 2000).

The water and energy resources need to be managed in tandem to adapt to climate change (Ernst & Preston, 2016; Scott et al., 2011; DOE, 2014). Traditionally, climate change adaptation is oriented to individual sectors rather than integrated or cross-sector adaptation. This overlooks the complex interdependencies between sectors; isolated adaptation in one sector can lead to increased vulnerabilities in the other. Some adaptation strategies, in response to climate change, can give rise to increased resource use and environmental degradation, for instance, as temperatures rise and water availability becomes uncertain, the demand for energy and water across all users may increase. The tradeoff lies in diverting water for increased energy demand versus conserving water for all other competing uses (Ernst and Preston, 2016; Scott et al., 2011). The tradeoffs within the energy-water nexus can be viewed as ‘energy security’ versus ‘sustainability’ or ‘greenhouse gas mitigation’ versus ‘water conservation’ and so on. Climate change makes these tradeoffs necessary and increasingly challenging, given the constraints and uncertainty around resources. This

dissertation focuses on the tradeoffs between greenhouse gas mitigation and water conservation in the energy-water-nexus. An illustrative example of this tradeoff is the water intensive hydraulic fracturing process to extract natural gas in water stressed regions such as Texas (Scott et al., 2011; Tidwell et al., 2013). Hydraulic fracturing or fracking has given rise to increased energy independence, economic development and reduction of greenhouse gas emissions in the United States however, it is a highly water intensive process requiring 2-9 million gallons of water per well (Scott et al., 2011) which becomes a particular concern in regions with uncertain water supply and abundance of natural gas reserves such as Texas (Nicot & Scanlon, 2012; Roy et al., 2012; Tidwell et al., 2013). Due to limited published literature around climate change and impacts on energy-water nexus in fracking (Scott et al., 2011; Tan & Zhi, 2016) particularly in Barnett, Texas, this dissertation takes an in-depth look into understanding the complexity of this nexus with a particular focus on the Barnett shale play in Texas, and its adaptation to climate change.

One way to understand the energy-water nexus within shale gas production and its environmental consequences is to use a systems approach. A well-established and widely used systems approach is Life Cycle Assessment (LCA) (Curran, 1996; Rebitzer et al., 2004; Pennington et al., 2004). Traditionally this tool is used to understand the sub-components of any product or process to quantify all the raw material and energy inputs and their environmental impacts at each stage of production (Curran, 1996). LCA is extremely useful in acquiring a snapshot of a process and is widely used in quantifying the energy and water footprints within shale gas production (Jiang et al., 2011; Grubert et al., 2012; Jiang et al., 2014; Nicot & Scanlon, 2012) and in understanding the energy-water-nexus and the inherent tradeoffs (Perrone et al. 2011; Bazilian et al., 2011). Nonetheless, this tool is limited in examining the uncertain energy and water futures in terms of technology, governance and other socioeconomic factors influencing the two sectors. In order to capture these uncertainties for the sake of developing accurate alternative adaptation options, LCA needs to be coupled with scenarios (Heijungs & Huijbregts, 2004; Mekonnen et al., 2016). Both Björklund (2002) and Huijbregts (1998) assert that scenario analysis combined with LCA can address various types of uncertainties within LCA and provide a range of outcomes important for decision-making.

As there may not be one optimal solution given the tradeoffs within the energy-water nexus, potential solutions can be identified by looking at various scenarios of energy pathways with respect to different technology pathways, each with its own level of greenhouse gas emissions and water consumption (Scott et al., 2011; Kriegler et al. 2012; Ghanadan & Koomey, 2005; Bazilian et al., 2011). The intensity of water use and energy dissipated depends on the technology adopted; the amount of energy used in desalination as the wastewater management option for produced water from fracking is much higher than energy needed in

transporting and injecting water in an aquifer. Using a coupled methods approach allows us to dig deep into the water and energy use within a select energy system and to understand the hot spots and opportunities that exist in making the system more sustainable and resilient. It also helps us in understanding the uncertainties around the future socioeconomic make up of the region in question and how the energy-water nexus will manifests itself in disparate futures with opportunities for climate change adaptation. This dissertation utilizes tools and methods towards that end. The aim is to demonstrate the complexities in the energy-water nexus and help manage the tradeoffs for decision and policy makers especially in the light of climate change where resource use must reflect greenhouse gas mitigation, efficiency in energy technologies, and sustainable water resources.

Research Objectives

The primary research objective of this dissertation is to understand the complex energy water nexus and the trade-offs involved in their co-management in order to optimize their interdependencies in the most sustainable way to adapt to climate change. This objective will be met by focusing on a region of Texas experiencing drought conditions and water stress (TWDB, 2017); the Barnett Shale in the Fort Worth Basin of Texas, which will allow us to understand the water and energy tradeoff offs when it comes to energy and water co-dependence in a given system, especially in the light of sustainability and adaptation to climate change. Three collaborative research manuscripts are developed to meet the research objectives and are presented as three chapters following an Introduction and summed up with a Conclusion. Each chapter answers a research question highlighted in the dissertation proposal and shown as follows:

Research Question 1:

How to explore alternative socioeconomic futures and identify socioeconomic challenges for impacts, adaptation and vulnerability, particularly in energy and water sectors, at subnational scales?

Research Question 2:

How can we quantify the energy and water flows to identify the tradeoffs in a hydraulic fracturing system in order to optimize the system to make it more sustainable?

Research Question 3:

How do we capture future uncertainties of a regional energy-water-nexus within hydraulic fracturing with respect to socioeconomic factors, influencing the two sectors, by using disparate scenarios and policy assumptions to determine the best adaptation options?

Summary of Approach

Chapter 1 develops sub-national and sectoral extensions of the global shared socioeconomic pathways (SSPs), as nested qualitative storylines, in order to identify future socioeconomic challenges for adaptation for the United States on national, regional and local scales. Future uncertainties around energy and water nexus can be captured by using socioeconomic scenarios for climate change adaptation research (Ebi et al., 2014; Mekonnen et al., 2016) and this dissertation leverages an existing scenario framework called the Shared Socioeconomic pathways (O'Neill et al., 2014b), and develops sub-national and sectoral extensions of these global SSP storylines in order to identify future socioeconomic challenges for adaptation for the U.S. Southeast. These narratives possess information about the socioeconomic factors including population and economic trends, technology assumptions and the evolution of energy and water sectors for several disparate scenarios for the southeastern United States and its sub-regions.

Chapter 2 quantifies energy, material and water flows in the hydraulic fracturing system by conducting a life cycle assessment of 'carbon footprint' (greenhouse (GHG) emissions) and 'water footprint' (water consumption) to understand the environmental impacts of energy and water use in the system. The GHG emissions are directly linked to climate change whereas the water consumption is a determinant of water scarcity. Tradeoffs exist within production systems such that a system, which has higher carbon footprint, has lower water footprint and vice versa (Mekonnen et al., 2016); this complicates setting priorities for overall environmental improvement. LCA helps quantify the 'carbon footprint' and the 'water footprint' of the process, and their impacts on the environment, which helps make decisions easier depending on whether the overall objective is to reduce greenhouse gas emissions or to conserve water. Life cycle assessment also supports carrying out different instances of the same process to understand the sensitivities of various input parameters on the environmental flows. LCA helps quantify all the energy and material inputs and to identify the tradeoffs especially if multiple instances of the same process are used with different technological assumptions, thus providing different environmental flows for the same process (Pasqualino et al., 2009; Lundie et al., 2004; Boer et al., 2007).

Chapters 3 combines the two frameworks developed in Chapters 1 and 2, by testing the nested SSPs for Texas, by developing shared policy assumptions and quantifying them as input parameters to the LCA model, to evaluate energy and technology pathways around adaptation of hydraulic fracturing and water use in Texas. The framework developed in Chapter 1is used to extend further the socioeconomic narratives to the state of Texas to include specific technology and policy assumptions around adaptation of the hydraulic fracturing sector with respect to the energy-water-nexus, within the context of each scenario. Socioeconomic scenarios of disparate development pathways can provide

alternatives to a given path and its associated tradeoffs, making it possible to avoid path dependence and to allow stakeholders and decision makers to evaluate all adaptation options before making long-term binding decisions. These tradeoffs are quantified using the model developed in Chapter 2 using the socioeconomic storylines and their associated technology and policy assumptions in a Prospective or futures oriented LCA.

The Conclusion synthesizes the main findings from the three chapters and discusses opportunities to use the research to improve future policy decisions related to climate change and energy-water nexus.

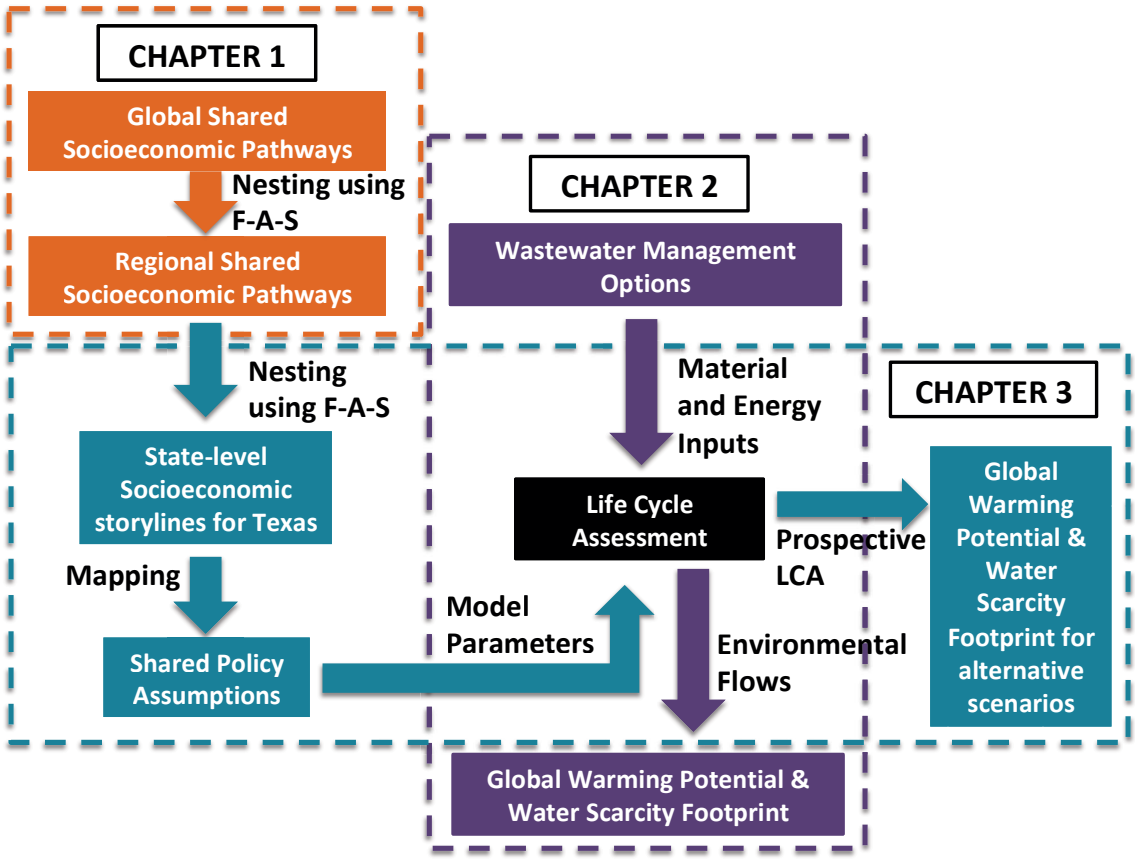

Figure 1. Conceptual Model of the Dissertation

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Chapter One - Extending The Shared Socioeconomic Pathways For Sub-National Impacts, Adaptation, And Vulnerability Studies

A version of this chapter was originally published by Syeda Mariya Absar and Benjamin L. Preston:

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The article is presented in its original form, formatted for this dissertation. Author was lead author and lead investigator on this study. Coauthor Benjamin L. Preston was the author's major thesis advisor. His guidance and revisions were instrumental in this publication.

Abstract

The exploration of alternative socioeconomic futures is an important aspect of understanding the potential consequences of climate change. While socioeconomic scenarios are common and, at times essential, tools for the impact, adaptation and vulnerability and integrated assessment modeling research communities, their approaches to scenario development have historically been quite distinct. However, increasing convergence of impact, adaptation and vulnerability and integrated assessment modeling research in terms of scales of analysis suggests there may be value in the development of a common framework for socioeconomic scenarios. The Shared Socioeconomic Pathways represents an opportunity for the development of such a common framework. However, the scales at which these global storylines have been developed are largely incommensurate with the sub-national scales at which impact, adaptation and vulnerability, and increasingly integrated assessment modeling, studies are conducted. The objective of this study was to develop sub-national and sectoral extensions of the global SSP storylines in order to identify future socioeconomic challenges for adaptation for the U.S. Southeast. A set of nested qualitative socioeconomic storyline elements, integrated storylines, and accompanying quantitative indicators were developed through an application of the Factor-Actor-Sector framework. In addition to revealing challenges and opportunities associated with the use of the SSPs as a basis for more refined scenario development, this study generated sub-national storyline elements and storylines that can subsequently be used to explore the implications of alternative sub-national socioeconomic futures for the assessment of climate change impacts and adaptation.

Introduction

The evolution of human systems is a key factor influencing societal vulnerability to climate variability and climate change (Denton and Wilbanks, 2014; IPCC, 2012). Future economic development pathways at global, national, sub-national,

and local levels, for example, will influence future emissions of greenhouse gases (Denton and Wilbanks, 2014), the exposure of human populations to climate variability and change (IPCC, 2012; Preston, 2013), and society's adaptive and mitigative capacities to reduce climate risk (Adger, 2007). Therefore, prognostic studies of the potential consequences of climate change should account for the non-stationarity of human systems and the uncertainty of future development pathways if they are to generate insights that are both credible and relevant for problem orientation and risk management (Berkhout et al., 2013; Preston et al., 2011). As future development pathways, globally and locally, are subject to some degree of irreducible uncertainty, scenarios are one of the most common approaches to representing future socioeconomic conditions and trends within integrated assessment modeling (IAM) (Edmonds et al., 2012; Nakićenović and Swart, 2000; Valverde, 2004) and climate change impacts, adaptation and vulnerability (IAV) research (Amer et al., 2013; van Ruijven et al., 2013; Varum and Melo, 2010).

To date, the IAM and IAV research communities have adopted different approaches to the development and use of socioeconomic scenarios, due to differences in research scales and objectives. The IAV community often develops scenarios that focus on context-specific aspects of socioeconomic systems that are focused on particular geographies or sectors (Birkmann et al., 2013; Brand et al., 2013; Kok et al., 2007; van Ruijven et al., 2014; Vervoort et al., 2014). Furthermore, there is often an element of stakeholder participation in the scenario development process to capture the values, preferences, and concerns of those that would be affected by, and have responsiblity for responding to, climate change and its consequences. Such scenarios are often fit-for-purpose, but as such may have little connection to global socioeconomic processes, and they may not be readily comparable(van Ruijven et al., 2013). For IAMs, quantiative socioeconomic scenarios represent critical modeling inputs. Yet, those inputs have traditionally been provided at relatively large-scale global or regional aggregations (Nakićenović and Swart, 2000). Furthermore, stakeholder participation in scenario development for IAMs has not been a priority and IAMs have been criticized for not explicilty incorporating qualitative aspects of social systems that give rise to market imperfections, institutional and informational constraints, and delayed policy implementation (Adger et al., 2008; Chambwerak et al., 2014; Ebi and Yohe, 2013; Klein et al., 2014). Nevertheless, IAMs provide a mechanism for the internally consistent modeling of future socioeconomic dynamics across space and time, and the IAM research community is directly involved in model intercomparison for alternative socioeconomic futures (e.g., Riahi et al., 2015).

Current trends in both IAV and IAM research suggest that their historically distinct scales and objectives may be converging. Investments by the U.S. Department of Energy and its national laboratories have focused on the development of regional IAM frameworks (de Bremond et al., 2014; Kraucunas et

al., 2014; Moss et al., 2013) that resolve the macroeconomic impacts of regional-(i.e., sub-national) scale climate impacts and policy responses while maintaing links to global-scale biophysical and economic processes (Thomson et al., 2014). Similar IAM frameworks in Europe have demonstrated the value of multi-scale integrated modeling that also incorporates stakeholder participation in scenario and model development (Harrison et al., 2013). Meanwhile, efforts such as the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Huber et al., 2014) and the Agricultural Model Intercomparsion Project (AgMIP) (Rosenzweig et al., 2014) are indicative of growing integration and collaboration within the IAV community toward consistent, multi-scaled impact modeling. Collectively, these developments are enhancing the capacity to, on one hand, incorporate the sub-national to local-scale context characteristically explored through IAV studies into IAMs, and, on the other hand, scale-up IAV methods and analyses to provide more comprehensive understanding and geographic coverage of potential impacts. This convergence between the IAM and IAV communities suggests there may be strategic advantages in the development and use of a common framework for socioeconomic scenarios.

The Shared Socioeconomic Pathways (SSPs), which, in conjunction with the Representative Concentration Pathways, comprise the parallel scenario process (Ebi et al., 2014; Kriegler et al., 2012; Moss et al., 2010; O'Neill et al., 2014b; O'Neill et al., 2012), represent an opportunity to develop such a common framework. The SSPs are a new framework for the generation of insights regarding the future implications of climate change that enables the integration of projections of future climate change from Earth system models, future socioeconomic conditions, and alternative climate policy assumptions (O'Neill et al., 2014b; O'Neill et al., 2012). The SSPs describe plausible alternative trends in the evolution of society and ecosystems over the course of the 21st century assuming no explicit policies to mitigate or adapt to climate change. As they were developed to reflect driving forces important to understanding climate outcomes, they do not include explicit assumptions about future emissions, or climate change impacts. In other words, they reflect key inputs that enable understanding of vulnerabilities that determine the magnitude and pattern of climate change risks, but those are derived from other analysis tools such as IAMs or climate impact models.

As with prior efforts to develop socioeconomic scenarios, such as SRES (Nakićenović and Swart, 2000), and the Global Environment Outlook (GEO) (UNEP, 2002, 2007), the SSPs have been explicitly designed for the global scale with the intent of subsequently developing sub-global and sectoral extensions to address specific research questions of interest to the IAM and/or IAV research communities (Birkmann et al., 2013; Ebi et al., 2014; O'Neill et al., 2014a; van Ruijven et al., 2013). Global, continental, or even national storylines and scenarios are often too coarse geographically to capture vulnerability and adaptive capacity, which are widely recognized as being place-based

phenomenon that are strongly, but not exclusively, influenced by local context (Kriegler et al., 2012). Information on socioeconomic futures at the sub-national scale may therefore be considered more relevant for IAV research and more legitimate for stakeholders and practitioners (Birkmann et al., 2013). Yet, there may be advantages to having such information linked to conditions and trends at the global scale that represent a common set of shared assumptions. For example, while global storylines and quantitative scenarios were developed as part of the Millennium Ecosystem Assessment (MA) (Carpenter, 2005), a range of sub-national assessments were also conducted that included storylines generated by various methods with varying degrees of consistency with the global storylines (Lebel et al., 2005). Similarly, in order for the IAV community, in particular, to capitalize on the opportunities presented by the SSPs, methods are needed to bridge the scale disconnect between the global SSP storylines and the sub-national scales at which much of the socioeconomic conditions that influence vulnerability, impacts, and adaptive capacity are relevant (see also Vervoort et al., 2014).

Here, we describe a method for developing sub-national and sectoral SSP storyline extensions for the U.S. Southeast as part of an effort to undertake climate impact modeling for the region's agriculture, water, and energy sectors that reflects uncertainty in future adaptive capacity. We apply an existing framework for the iterative development of socioeconomic storylines that span multiple spatial scales in order to generate a series of sub-national SSP storylines and quantitative indicators for the U.S. Southeast (Kok et al., 2006a; Rotmans et al., 2000). In so doing, the objectives were to a) identify potential challenges associated with using the global SSPs for nested storyline development, b) explore a specific method for managing these challenges, and c) discuss subsequent applications in which such storylines can be operationalized in both qualitative and quantitative IAV studies.

Conceptual Framework for Nested Storyline Development

The Shared Socioeconomic Pathways

The Shared Socioeconomic Pathways (SSPs) are the next generation of socioeconomic storylines for climate change research and assessment, emerging from the parallel scenario process (Moss et al., 2010). The basic SSPs are a set of global qualitative storylines and allied quantitative scenarios framed around various combinations of socioeconomic conditions and trajectories that create challenges to greenhouse gas mitigation and/or climate adaptation (Figure 2) all tables and figures are located in the appendix (Kriegler et al., 2012; O'Neill et al., 2014a, b; O'Neill et al., 2012). The SSP1 (Sustainability) storyline assumes a future global socioeconomic development trajectory characterized by

substantial gains in sustainability. As such, there are relatively low challenges for both mitigation and adaptation. In contrast, SSP3 (Regional Rivalry) assumes a breakdown in international cooperation and globalization leading to high challenges for both mitigation and adaptation. SSP4 (Inequality) and SSP5 (Fossil-fueled Development) explore permutations where there are high challenges along just one dimension of mitigation or adaptation, while SSP2 (Middle of the Road), is largely a business-as-usual trajectory. The SSPs are formulated independent of any explicit climate change projections or mitigation and adaptation policies, but rather represent socioeconomic factors that, for any given policy objective, would make mitigation or adaptation more achievable or difficult. The basic SSPs therefore represent socioeconomic boundary conditions for key driving forces that can inform subsequent extensions of the SSP storylines to add sub-national and/or sectoral context as needed for particular research activities and/or stakeholder needs (Ebi, 2013; O'Neill et al., 2014a, b). However, the SSPs have emerged relatively recently, and the development of such extended storylines is in a nascent state. Hence, this study explores one approach to developing extended storylines in a manner that retains internal consistency across geographic scales.

Bridging Scales in Socioeconomic Scenario Development

Various methodologies appear in the literature for developing socioeconomic scenarios for IAV and IAM research. These reflect different epistemologies and have different strengths and weaknesses for specific applications and desired outcomes. Generally, the various methodologies can be framed as top down and bottom up approaches (Biggs et al., 2007; Holman et al., 2005; Kok et al., 2006a; Sleeter et al., 2012), which reflect different entry points for scenario development with respect to scale, audience, and use. Bottom up approaches may, for example, employ participatory scenario development techniques to generate qualitative storylines for the study domain of interest, (Birkmann et al., 2013; Kok et al., 2006a; Kok et al., 2006b), and then, if relevant, link those scenarios to conditions and trends at more global scales (Holman et al., 2005; Sleeter et al., 2012). Such approaches allow maximum flexibility for scenario authors as they are unconstrained by prior efforts. However, although such storylines potentially can be mapped back to global level scenarios based on common underlying themes, the ad hoc generation of multiple independent storylines may create significant challenges with respect to making comparisons across storylines or storyline groupings (Zurek and Henrichs, 2007). In contrast, top down approaches use, often global, scenarios as boundary conditions for more regionalized scenarios at other scales (Kok et al., 2006b), and are often accompanied by the quantification of key variables. Top down approaches are best suited to situations in which a priori global scenarios are considered a desirable starting point for scenario development at other scales. This would include situations in which there is already some legitimacy or process associated with a set of scenarios; where there is interest in exploring cross-

scale interactions and teleconnections; or where one seeks to maintain consistent assumptions across multiple studies (Biggs et al., 2007). Generating scenarios at finer spatial scales can be achieved by either downscaling approaches, which are particularly relevant for generating higher resolution around quantitative scenario elements (e.g., GDP, population, land use) (van Vuuren et al., 2007; van Vuuren et al., 2010), or nesting approaches in which one seeks to develop qualitative storylines that provide increasingly rich socioeconomic context at increasingly regionalized scales (Kok et al., 2006b; Leadley et al., 2010). As nested qualitative storylines are not limited in terms of the scope of socioeconomic elements they contain, they enable one to describe a broad set of socioeconomic processes, conditions, and interactions that are relevant for representing societal vulnerability and adaptive capacity.

Given the relationship between sub-national development trajectories and global trajectories is uncertain, there are two idealized assumptions one can make. First, sub-national trajectories may evolve in concert with global trajectories. For example, rapid population growth at the global scale may be reflected at sub-national scales, although what constitutes rapid growth may vary between scales. Alternatively, sub-national trajectories may evolve independently of global trajectories, in which case sub-national development is unbounded by global development pathways. These two assumptions translate into two general approaches to developing nested storylines (Figure 3). The first assumption can be represented by a ‘one-to-many’ nesting in which the storyline at each scale is consistent with a multitude of storylines at other scales (Biggs et al., 2007; Zurek and Henrichs, 2007). The one-to-many approach is perhaps most faithful to future uncertainty given inevitable surprises. However, it results in unconstrained growth in potential storylines as one shifts from one scale to another. This can result in a) a suite of storylines too numerous to effectively manage or communicate as well as b) redundancy among storylines variants. The second assumption can be represented by a ‘one-to-one’ nesting of storylines in which each storyline at a given geographic scale manifests at the next lower scale as a single storyline with fully consistent assumptions on drivers and scenario logics as the higher scale scenarios, but with enhanced context (see also Zurek and Henrichs, 2007). The ‘one-to-one’ approach to nesting is more expedient, but this is achieved by artificially constraining the ways in which futures evolve across different scales. This may be particularly problematic in scenario development processes involving stakeholder participation, as it reduces the opportunities for stakeholders to shape the manner in which futures are explored (Biggs et al., 2007). Nevertheless the one-to-many approach allows the exploration of disparate futures provided the parent global scenarios themselves are disparate themselves. This one-to-one approach was therefore selected as a means of developing nested storylines for current study based on the SSPs.

The Factor-Actor-Sector Framework

The method used to develop nested socioeconomic storylines or storyline extensions, is called the Factor-Actor-Sector framework (Kok et al., 2006b). Within this framework, a sector represents a sub-component of a national or social system. An actor represents an individual or organization of individuals with the capacity to effect and/or influence change. A factor represents an aspect of a social or natural system around which there are broad policy issues of particular interest (Kok et al., 2006b). This framework was first used during the VISIONS project funded by the European Commission to develop a range of alternative scenarios for European sectors as guidance for setting mid-term and long-term strategies for sustainable development both at the European and sub-national scales (Rotmans et al., 2000). The Factor-Actor-Sector framework was selected for the current study for its ability to address the complexity of socioeconomic systems in a systematic and structured manner and to enable investigators to define a priori the relevant aspects of socioeconomic futures. For example, by design, the global SSPs are comprised of succinct descriptions on a wide range of factors in order to avoid overly-prescribing future socioeconomic conditions in ways that would limit their usefulness for diverse applications. However, as a consequence, the global SSP storylines lack descriptions of some elements that are often considered relevant to IAV research such as the status and trends of certain sectors and/or the roles of specific actors and governance networks. Explicit identification of these elements is an essential starting point for the Factor-Actor-Sector framework. By deconstructing socioeconomic pathways into these elements, the framework creates entry points for global SSP storyline elements while also enabling the exploration of other aspects of socioeconomic futures. In so doing, the Factor-Actor-Sector framework facilitates the development of internally consistent, multi-scaled storylines, as each element at a given scale can be generated in a manner that directly links to like elements at other scales (Kok et al., 2006b).

Storyline Development

Global Storyline Elements

The first step in developing the nested storylines was the articulation of a core set of factors, actors, and sectors (referred to here as storyline elements), that were relevant across multiple spatial scales and to the study context (Table 1.1; Figure 4) all tables and figures are located in the appendix. Because sufficient resources were not available in the current study to enable a robust, multi-scaled, participatory scenario development process, the identification of relevant storyline elements was achieved through literature review. For factors, this process was informed by elements described in the global SSP storylines as well as by examining the factors that are commonly incorporated in other scenario exercises or used as input in IAMs or integrated assessment more broadly

(IIASA, 2012b; Kok et al., 2006a; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O'Neill et al., 2012; UNEP, 2007). This enabled consideration for qualitative elements of socioeconomic systems that pose challenges to adaptation that are not routinely represented explicilty in IAMs or other top down modeling and assessment methods. For example, although specific actors are often not articulated in scenarios or in IAM experiments, a small set of actors was identified that influence the governance of different resources (e.g., public versus private institutions). Sectors were defined based upon common inclusion in global assessments such as the IPCC Working Groups II and III, common outputs from integrated assessment models, or because they have been identified as having significant geopolitical implications. The above criteria also capture those sectors that were particularly relevant for future applications of the nested storylines in the U.S. Southeast, specifically, energy, water, and agriculture.

To implement the global Factor-Actor-Sector framework, the five global SSP qualitative storylines were mapped to the defined factors, actors, and sectors (Figure 4) (O'Neill et al., 2014b; O'Neill et al., 2012). The SSP narratives were reviewed and language from each that provided context at the global scale for any of the defined elements was extracted and recorded in a database. Hence, each element was associated with a brief description of condition or trend as defined by the global SSP narrative. As the set of defined factors, actors, and sectors was generally broader than that which is described by the global SSPs, several factors and, particularly, actors and sectors remained undefined. Because a concerted effort was made to preserve the global SSP storyline elements intact as they were originally prescribed, and because the ultimate interest was in sub-national scale context, no attempt was made to fill these gaps in the definition of specific factors, actors, or sectors.

National Storyline Elements

The first level of storyline nesting consisted of the development of national storyline elements based on the global elements (Figure 4). In order to constrain the number of scenarios for consideration and to focus the nesting of socioeconomic storylines around challenges for adaptation, this study used four of the five global SSPs storylines, excluding SSP4 (Inequality) (Figure 2). The remaining four storylines span the continuum of low (SSP1 and SSP5), medium (SSP2), and high (SSP 4) challenges to adaptation. Both SSP1 and SSP5 were examined because they achieve such low challenges for adaptation through diametrically opposed development pathways. As a result, the implications for some of the scenario elements in SSP5 (e.g., biodiversity/conservation) run counter to the overall narrative of low challenges for adaptation. Meanwhile, because SSP5 and SSP4 represent high challenges to mitigation, they can be consistently applied in conjunction with an RCP8.5 scenario to juxtapose differential challenges to adaptation under more pessimistic scenarios of climate

change. While the social inequality under SSP4 represents a classic indicator of low adaptive capacity, its low challenges vis-à-vis mitigation suggest it is less consistent with RCP8.5. In addition, the plausibility of SSP4, where future challenges to mitigation are low, but actors experience difficulties in the pursuit of adaptation, would appear less plausible than the other SSP storylines, particularly for developed nations such as the United States. As the relevant factors, actors, and sectors changed when the analysis lens focused on the United States, some elements considered in the global SSP storylines were dropped and not explored further at other scales. For example, while the Millennium Development Goals represent a key development metric for developing nations, they have little direct relevance to future U.S. socioeconomic development pathways. In addition, while agriculture and forestry was included as an aggregate Sector in the definition of global SSP elements, it was separated into two components of agriculture and forestry for the national level factors. Those elements that were retained were subsequently defined for the U.S. in a manner consistent with tight coupling to the global SSP narratives.

This process posed two methodological challenges. First, a process was required for defining national level storyline elements that corresponded with the global elements, despite the fact that the global SSP narratives lack detailed information at the national scale (although some national level data for the variables of population, GDP, and urbanization were available through the SSP data base (IIASA, 2012a). Second, storyline elements that were not articulated in the global SSP narratives had to be defined. Rather than develop this content purely de novo, these challenges were addressed through a review of peer reviewed and grey literature to identify existing storylines, scenarios, and allied information regarding current and future trends in different factors, actors, and sectors (Figure 4; Table 1.2). When relevant storylines or scenarios were identified, these were categorized based on their consistency with the global SSP storyline elements. For example, factors associated with the SSP5 (Fossil-fueled Development) storyline reflect high rates of U.S. population growth and economic development, but those trends are coupled to modest rates of technological change, particularly in the energy sector. In developing national storylines, U.S. demographic scenarios (e.g., Bierwagen et al., 2010; Guarneri, 2009; IIASA, 2012a, b; O'Neill et al., 2014b; O'Neill et al., 2012; USCB, 2012a, b), economic scenarios (e.g., MGI, 2011; O'Neill et al., 2014b; O'Neill et al., 2012; UNEP, 2007; WEF, 2010), and technology scenarios (e.g., IEA, 2012; Mintzer et al., 2003; O'Neill et al., 2014b; O'Neill et al., 2012; RF and GBN, 2010; UNEP, 2007) were reviewed to identify scenarios for these elements that were consistent with the Fossil-fueled Development storyline.

In addition to maintaining vertical consistency in a single storyline element across scales, efforts were also made to maintain horizontal consistency among different elements within the same scale. Factors such as population, GDP, and

technology will evolve over time in tandem. Similarly, the future evolution of different U.S. sectors will be dependent upon future trajectories of global and U.S. factors. Hence, the development of content for each storyline element required ongoing consistency checks with other elements. For example, SSP1 (Sustainability) characterizes future global society as one associated with rapid rates of technological change, which ultimately affects the evolution of specific sectors such as energy and agriculture. Therefore, in using existing national scenarios of the energy (e.g., EIA, 2012a, b; Mintzer et al., 2003; O'Neill et al., 2014b; USDOS, 2010) and agriculture (e.g., ERS, 2011; IFTF, 2011; UNEP, 2007) sectors to develop national storyline elements for different SSPs, content for SSP1 for these sectors was derived from those existing sectoral scenarios that suggested similarly rapid rates of technological change.

Sub-National Storyline Elements

For sub-national storylines, the factors and actors considered in storyline development remained the same as those for the national storylines, but for the sectors, the focus narrowed to elaborate storyline elements for the three sectors considered most relevant to the study focus: energy, water and agriculture (Table 1.1). As in the case of national storylines, the sub-national storyline elements were developed using national storylines and scenarios that contained sub-national detail as well as more state-based information (Table 1.2). Generally, identifying sources of information and scenarios regarding future factors, actors, and sectors at the sub-national scale was more challenging. As a consequence, the development of storyline elements was often based upon extrapolating the current socioeconomic context of the region while attempting to maintain vertical and horizontal consistency with other storyline elements.

Although sub-national storyline elements were largely based on qualitative information, some quantitative indicators were developed to better understand the relative trends, magnitudes and dynamics of key factors within the region. These quantitative indicators were developed for state population and GDP by spatially disaggregating the U.S. population (IIASA-WIC v9) and GDP (IIASA-GDP v9) projections within the International Institute for Applied Systems Analysis (IIASA) SSP database version 0.93 (IIASA, 2012a) to the state level using the Integrated Climate and Land Use Scenarios (ICLUS) sponsored by the U.S. Environmental Protection Agency (Bierwagen et al., 2010) and Bureau of Economic Analysis data (BEA, 2013), respectively. For population, the global SRES storylines associated with individual ICLUS scenarios were first paired with the global SSP storylines to identify SRES/SSP pairings that were generally consistent. Hence, SSP1, SSP2, SSP3, and SSP5 storylines were paired with the ICLUS SRES B1, Base case, A2, and A1 scenarios, respectively (see also Nakićenović and Swart, 2000). The ICLUS population scenarios were then used to calculate the proportion of future growth in total U.S. population attributable to each U.S. county and state in 10-year time steps from 2010 to 2100. These

proportions were then used as scaling factors, which were applied to the population increases generated for the corresponding SSP population scenarios for the United States in IIASA's SSP database. For state GDP scenarios, the average percentage contribution of each state to national GDP growth for 15 recent years (1997–2011) was calculated from the U.S. Bureau of Economic Analysis data (BEA, 2013) and these percentages were then used to disaggregate IIASA's SSP 21st century national U.S. GDP scenarios to state level GDP estimates.

Results

The method applied here generated a number of outputs. First, development of storyline elements for factors, actors, and sectors at the global, national, and sub-national level across the four SSPs resulted in a database with details regarding each storyline element, which enables one to compare storyline elements across different SSP assumptions and scales (Figure 5). For example, comparing SSP1 and SSP5 storyline elements for the water sector at each scale illustrates the evolution of information as one shifts from the global to the sub-national scale as well as the similarities and differences between the different SSPs with respect to outcomes and the pathways by which those outcomes are realized (Figure 6). By design, the SSPs provide only cursory information on the water sector at the global scale, with both SSP1 and SSP5 indicating that access to safe drinking water is expanded. They emphasize slightly different mechanisms by which such achievements are realized (achievement of MDGs in SSP1 while SSP5 emphasizes large-scale infrastructure investments), but these mechanisms are not mutually exclusive. At the national scale, the issue of water is broadened beyond just drinking water availability. Both SSP1 and SSP5 emphasize integrated water management and efficiency measures, yet SSP5 suggests a greater intensity of water resource development to meet the high levels of population growth and economic development. At the sub-national level, such distinctions become more evident. While SSP1 highlights sustainable water management practices, efficiency, and equity, SSP5 focuses on increasing privatization and resource development in order to meet demand and drive water use toward its highest value. Hence, both storylines suggest a future of water sufficiency through development pathways that enable adaptation, in contrast with other storylines such as SSP3 where capacity in the water sector is lower. However, the implications of SSP1 and SSP5 for long-term sustainability are not equivalent, and these two storylines imply significant differences in patterns of investment, governance, and the culture of water.

The use of quantitative scenarios to explore the key driving forces of population and demography at the sub-national level provided additional context regarding the manner in which different socioeconomic pathways manifest in the U.S. Southeast. For example, population growth of states of the U.S. Southeast was projected to peak during the 21st century in SSP1, SSP2, and SSP3, with that

peak arriving by approximately 2030 for SSP3 and toward the end of the century in SSP1 and SSP2 (Figure 6). Much of the change in the population at the sub-national level is associated with Florida and Texas – the two states that have the largest populations at present and are projected to account for a significant fraction of future population growth. These two states also account for a significant fraction of U.S. and Southeast GDP. However, the 21st century temporal dynamics of GDP scenarios for a given SSP are similar across the states. For SSP1 and SSP2, there is steady, but modest and linear, growth in GDP over the 21st century. Growth in GDP under SSP3 is more constrained and has largely plateaued by 2100. In contrast, GDP under SSP5 grows exponentially, reaching levels that are several-fold higher than those observed for other SSPs. These methods resulted in population and GDP scenarios for U.S. Southeast states that scale directly to the U.S. scenarios within the IIASA database, but with the sub-national distribution determined by more localized trends and dynamics. However, at the aggregate state level, where gradients between urban and rural landscapes are masked, these scenarios are dominated by the national SSP scenarios and the historical distribution of population and GDP among U.S. states. This implies some degree of path dependence in future rates of change.

The database of storyline elements is extensive and therefore difficult to use to rapidly compare and contrast elements associated with different SSPs and/or scales. As such, a synthesis was conducted that focused on identifying the implications of each storyline element regarding challenges for adaptation (Figure 7). Storyline elements could be seen as creating moderate or large opportunities for adaptation, moderate or large challenges for adaptation, or neutral. In addition, factors reflect not just status but also trajectories, and thus factors have dual characteristics of both a trajectory (i.e., growth versus decline) as well as challenges to adaptation (i.e., moderate versus large). For example, SSP1 is associated with enabling conditions that pave the way for reductions in greenhouse gas emissions. Hence, the trajectory of the factor of emissions indicates a decline at the sub-national scale, which is interpreted as an increase in adaptive capacity under the assumption that lower emissions reduce the magnitude of future climate change to which society must adapt. In contrast, SSP5 is associated with high emissions growth thus poses greater challenges for adaptation. The synthesis also enables the rapid comparison of the implications of different SSP storylines at different scales. The storyline elements of SSP3 generally have a negative influence on adaptation across most of the factor, actors, and sectors. In contrast, most elements are positive under SSP1. It is also important to note that the trajectories of factors have different implications for adaptation under different storylines. At the sub-national scale, both SSP1 and SSP2 are associated with moderate growth in GDP. This has a positive influence on adaptive capacity under SSP1, under the assumption that economic growth helps to enable social, economic, and technological transitions associated

with more sustainable futures. In contrast, under SSP2, modest GDP growth in the absence of an emphasis on sustainable development is associated with higher adverse externalities that reduce the overall opportunities for adaptation.

In addition to the synthesis, the individual storyline elements at the sub-national scale were integrated to develop sub-national storylines that act as extensions of the global SSP storylines (Appendix). However, they do not capture all aspects of each storyline element and thus reflect a generalized vision for the region, but with a particular emphasis on the priority sectors of agriculture, water, and energy. In conjunction with the storyline element database and the storyline element synthesis, these sub-national storylines represent different tools for defining socioeconomic boundary conditions at the sub-national level for subsequent IAV applications. Nevertheless, the qualitative nature of the storyline elements and storylines allows some degree of flexibility for further modification or extension to suit specific needs.

Discussion

The global SSP storylines and the ongoing process to expand their relevance for diverse applications represent a new opportunity to routinize the consideration of future socioeconomic conditions and pathways in climate change research and assessment (van Ruijven et al., 2013). The development of extensions of the global SSPs for different regions and/or sectors is an inherent component of the SSP framework. However, in so doing, two challenges must be addressed: a) the scale discordance challenge associated with using the global SSPs at sub-global scales (Moser, 2000; van Ruijven et al., 2013; Zurek and Henrichs, 2007) and b) the information gap challenge created by the lack of detailed information on some factors, actors, or sectors that may be relevant for SSP extensions. As illustrated here, the Factor-Actor-Sector framework provides a structured process for addressing these challenges. The explicit articulation of factors, actors, and sectors allows one to prioritize key storyline elements and manage consistency checks among different elements and across different scales. It is also sufficiently flexible to enable the incorporation of a broad array of information sources to facilitate the development of sub-national and/or sectoral SSP extensions. For example, the current study mapped existing national and sub-national scenarios and storylines for different factors, actors, and sectors to the SSP pathways. In so doing, the resulting storyline elements were both consistent with the global SSPs as well as existing perspectives on future U.S. socioeconomic pathways. This approach of using literature review to facilitate the development of SSP extensions could, however, be readily accompanied by, or replaced with, participatory scenario processes where stakeholders drive the development of SSP extensions (Carlsen et al., 2012; Harrison et al., 2013; Kok et al., 2006a). Hence, the Factor-Actor-Sector framework represents a potentially

useful vehicle for structuring alternative mechanisms for extending the global SSPs.

Nevertheless, the application of the Factor-Actor-Sector framework also revealed challenges associated with nesting qualitative storylines within the SSPs. First and foremost, there is the question of what constitutes consistency between or within scales with respect to storyline elements. Zurek and Henrichs (2007) define consistent scenarios as being comprised of common boundary conditions, assumptions, and drivers. In this context, the national and sub-national storyline extensions developed here meet the criteria for consistency due to their adherence to the SSP logic framework and their representation of the various driving forces reflected in the global SSP storylines. However, given the global SSP storylines were, by design, developed to accommodate a range of futures, a diverse array of national or sub-national storyline elements could be considered to be consistent with any given SSP (O'Neill et al., 2014b). Those elements that were developed in the current study are therefore just one possible realization, and thus the nested storylines do not explore all the possible ways in which a given global SSP could manifest at the national or sub-national level. A second related challenge is that nesting process relies heavily on normative judgments, even when guided by additional literature or stakeholder participation. Hence, it would be difficult for two parallel applications of the Factors-Actors-Sectors framework to generate exactly the same nested storylines, although variants of a given SSP storyline should be recognizable as such. This suggests there may be trade-offs between flexibility and reproducibility, despite both being desirable features of scenario development methods. In contrast, the implementation of the global SSP storylines in an IAM provides a process-based and reproducible mechanism for evaluating socioeconomic responses to alternative boundary conditions. A third challenge is that the qualitative sub-national SSP storyline extensions may be difficult to operationalize within quantitative IAM or IAV modeling frameworks. Further interpretation and translation may be required to generate additional quantitative indicators that can be used as model inputs. These various challenges reflect the need to carefully consider the appropriateness of the method for developing SSP extensions and the potential value in exploring alternative methods.

While the current study reports the development of nested storylines for the U.S. Southeast, those storylines are not an end in themselves. Rather, the intent is to use these storylines for representing alternative socioeconomic pathways in the modeling of climate change impacts on the region, and key sectors at the land, water, energy nexus. To this end, the storylines help frame the selection of opportunities and constraints associated with adaptation of these sectors, including technological innovation and management practices that can be parameterized in crop, water resources management, and energy system models. This leads, however, to an additional consideration in the development

of SSP extensions, which is their integration with scenarios of future climate conditions to explore the joint implications of both climatic and socioeconomic change for impacts, adaptation, and vulnerability. The Scenario Matrix Architecture (SMA) is a key feature of the "parallel process" of scenario development in which socioeconomic storylines developed under the SSP framework are integrated with climate scenarios based on general circulation or regional climate models forced by the RCP scenarios (Ebi et al., 2014; Eom et al., 2013; Moss et al., 2010; van Ruijven et al., 2013; van Vuuren et al., 2014; van Vuuren et al., 2012). The issue of whether socioeconomic challenges to adaptation associated with a given SSP can truly be considered to exist independent of the rate and magnitude of climate change is an open question worthy of consideration and deliberation in the application of the SMA. For example, the conventional development pathway implied by SSP5 implies a greater likelihood of significant climate change and adverse impacts, which could pose a negative feedback on development, posing greater challenges for adaptation than are implied in SSP5. Meanwhile, the sustainable development pathway of SSP1 seems inconsistent with a world in which RCP8.5 also transpires. Hence, while the SMA provides some flexible conceptual guidance for the integration of SSPs with scenarios of climate change for the purposes of IAV research, additional work is needed to enable the operationalization of the SMA in ways that are internally consistent. Development of a suite of case studies that illustrate alternative ways in which the SMA can be implemented at multiple scales using a range of different climate and socioeconomic scenarios and storylines will be an important process in learning how the SSPs can be usefully applied by the IAV community.

Conclusions

The SSP framework for the development of socioeconomic storylines and scenarios represents a valuable opportunity for the consistent treatment of alternative assumptions regarding socioeconomic development and climate change within the climate change research community. Nevertheless, ongoing differences in information needs as well as research epistemologies associated with the Earth system modeling, IAM, and IAV communities suggest that each will need to be an active participant in determining ways by which it can effectively engage the parallel process and the emerging scenario frameworks. For the IAV community, the SSPs can provide a common scenario platform that still enables researchers and practitioners to develop place-based and/or sector-specific understanding of climate change consequences. Before this can happen, however, methods (or a portfolio of methods) must be developed that enable researchers and practitioners to effectively use the SSP framework across a range of geographic scales. The development of nested storylines using approaches such as the Factor-Actor-Sector framework is one approach to achieving this end. Nevertheless, as illustrated in this study, the development of

nested storyline elements and storylines invariably involves normative judgments of researchers and/or stakeholders. Therefore, no two attempts at extending the SSPs for regional or sectoral applications are likely to be identical. Such conceptual flexibility helps to align scenario development processes to assessment goals, which can be highly varied. A key test of the SSPs may therefore be the extent to which they can be successfully applied in disparate contexts while still remaining generally recognizable. However, additional case studies (e.g., Vervoort et al., 2014) with other methods are needed to evaluate the conditions under which the SSPs are useful in bridging scales in socioeconomic boundary conditions as well as for integration into the SMA under the parallel process.

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Appendix 1.1 – Tables and Figures

Table 1.1 Factors, Actors and Sectors for global, national and sub-national storyline development

	Global	Global	National	Sub-National
Factors	Demographics	●	●	●
	Globalization	●	●	–
	Economy/GDP	●	●	●
	Consumptive Behavior	●	●	●
	Technology	●	●	●
	Land use	●	●	●
	Biodiversity/conservation	●	●	●
	Equity	●	●	●
	MDGs	●	–	–
	Emissions	●	●	●
Actors	Public Institutions	●	●	●
	Private Institutions	●	●	●
	Civil Society	●	●	●
Sectors	Energy	●	●	●
	Water	●	●	●
	Agriculture & forestry	●	–	–
	Agriculture	–	●	●
	Forestry	–	●	–
	Transport	●	●	–
	Public Health	●	●	–
	Education	●	●	–
	Service	●	●	–
	Defense	●	●	–

Table 1.1 Continued

	Global	Global	National	Sub-National
	Entitlements	●	●	–
	Manufacturing	●	●	–
	Banking/Finance	●	●	–
	Natural Resource Extraction	●	●	–

Table 1.2. Information sources used in the development of storylines elements

	Storyline Element	Global	National	Sub-national
Factors	Demographics	(O'Neill et al., 2014b; O'Neill et al., 2012)	(Bierwagen et al., 2010; Guarneri, 2009; IIASA, 2012a, b; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O'Neill et al., 2012; UNEP, 2007; USCB, 2012a, b)	(Bierwagen et al., 2010; IIASA, 2012a, b; Mackun, 2011)
	Globalization	(O'Neill et al., 2014b; O'Neill et al., 2012)	(Mintzer et al., 2003; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O'Neill et al., 2012; UNEP, 2007; WEF, 2010)	–
	Economy	(O'Neill et al., 2014b; O'Neill et al., 2012)	(CBO, 2014; IIASA, 2012a, b; Nakićenović and Swart, 2000; UNEP, 2007; USBEA, 2013; USBLS, 2012, 2013; WEF, 2010)	(Coakley et al., 2009; USBEA, 2013)
	Consumptive Behavior	(O'Neill et al., 2014b; O'Neill et al., 2012)	(Mintzer et al., 2003; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O'Neill et al., 2012; RF and GBN, 2010; UNEP, 2007)	(EIA, 2012a, b)
	Technology	(O'Neill et al., 2014b; O'Neill et al., 2012)	(EIA, 2012a; Mintzer et al., 2003; Nakićenović and Swart, 2000; RF and GBN, 2010; UNEP, 2007; WEF, 2010)	(IEA, 2012)
	Land use	(O'Neill et al., 2014b; O'Neill et al., 2012)	(Bierwagen et al., 2010; O'Neill et al., 2014b; O'Neill et al., 2012; UNEP, 2007)	(Bierwagen et al., 2010; MGCSCI, 2013)
	Biodiversity/conservation	(O'Neill et al., 2014b; O'Neill et al., 2012)	(Leadley et al., 2010; O'Neill et al., 2014b; O'Neill et al., 2012; UNEP, 2007; WEF, 2010)	(Keddy, 2009; NWF and SELC, 2013)

Table 1.2 Continued

	Storyline Element	Global	National	Sub-national
	Equity	(O'Neill et al., 2014b; O'Neill et al., 2012)	(IAF, 2008, 2011; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O'Neill et al., 2012; UNEP, 2007)	(Oxfam, 2009)
	MDGs	(O'Neill et al., 2014b; O'Neill et al., 2012)	–	–
	Emissions	(O'Neill et al., 2014b; O'Neill et al., 2012)	(EIA, 2012a, b; Mintzer et al., 2003; Nakićenović and Swart, 2000; UNEP, 2007; USDOS, 2010)	(EIA, 2012a, b)
Actors	Public Institutions	–	(Mintzer et al., 2003; O'Neill, 2014; O'Neill et al., 2012; RF and GBN, 2010; UNEP, 2007)	(IEA, 2012; UNEP, 2007)
	Private Institutions	–	(Mintzer et al., 2003; RF and GBN, 2010; UNEP, 2007)	(Mintzer et al., 2003; RF and GBN, 2010; UNEP, 2007)
	Civil Society	–	(Mintzer et al., 2003; RF and GBN, 2010; UNEP, 2007)	(Mintzer et al., 2003; RF and GBN, 2010; UNEP, 2007)
Sectors	Energy	(O'Neill et al., 2014b; O'Neill et al., 2012)	(EIA, 2012a, b; Mintzer et al., 2003; USDOS, 2010)	(EIA, 2012a, b; IEA, 2012; Mintzer et al., 2003; NWF and SELC, 2013)

Table 1.2 Continued

	Storyline Element	Global	National	Sub-national
	Water	(O'Neill et al., 2014b; O'Neill et al., 2012)	(Li et al., 2011; Roy et al., 2005; Roy and Chen, 2011; Roy et al., 2012; Roy et al., 2010; UNEP, 2007)	(Li et al., 2011; Roy et al., 2005; Roy and Chen, 2011; Roy et al., 2012; Roy et al., 2010)
	Agriculture & forestry	(O'Neill et al., 2014b; O'Neill et al., 2012)	–	–
	Agriculture	–	(ERS, 2011; IFTF, 2011; UNEP, 2007)	(Malcolm et al., 2012)
	Forestry	–	(UN, 2012; UNEP, 2007)	–
	Transport	–	(EIA, 2012a, b)	–
	Public Health	(O'Neill et al., 2014b; O'Neill et al., 2012)	(IFTF, 2008; Makuc, 2008)	–
	Education	(O'Neill et al., 2014b; O'Neill et al., 2012)	(Anderson et al., 2012; Facer and Sandford, 2010; OECD, 2008, 2009)	–
	Service	(O'Neill et al., 2014b; O'Neill et al., 2012)	(CBO, 2014; USBLS, 2013)	–
	Defense	–	(NIC, 2012; USDOD, 2010, 2014)	–
	Telecommunications	–	(IGF, 2012; Lopez, 2012)	–
	Entitlements	–	(CBO, 2014; CMMS, 2012; IAF, 2011)	–

Table 1.2 Continued

	Storyline Element	Global	National	Sub-national
	Manufacturing	–	(MGI, 2011; PWC, 2012; UNEP, 2011)	–
	Banking/Finance	–	(WEF, 2010)	–
	Natural Resource Extraction	–	(UNEP, 2007; WEF, 2010)	–

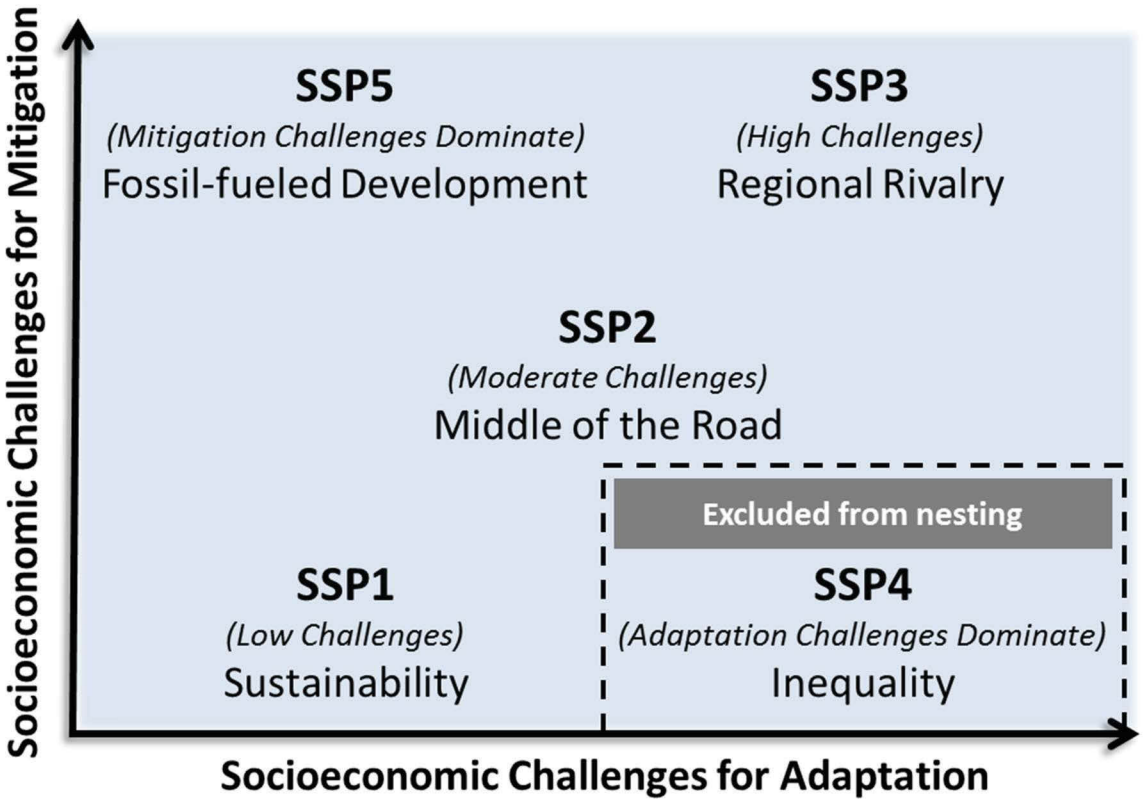

Figure 2. Logic framework for the shared socioeconomic pathways

The various illustrative SSP pathways (SSPs 1–5) occupy different positions within the socioeconomic uncertainty space defined by challenges for mitigation and challenges for adaptation (see also Kriegler et al., 2012; O'Neill et al., 2014a, b; O'Neill et al., 2012; van Vuuren et al., 2014).

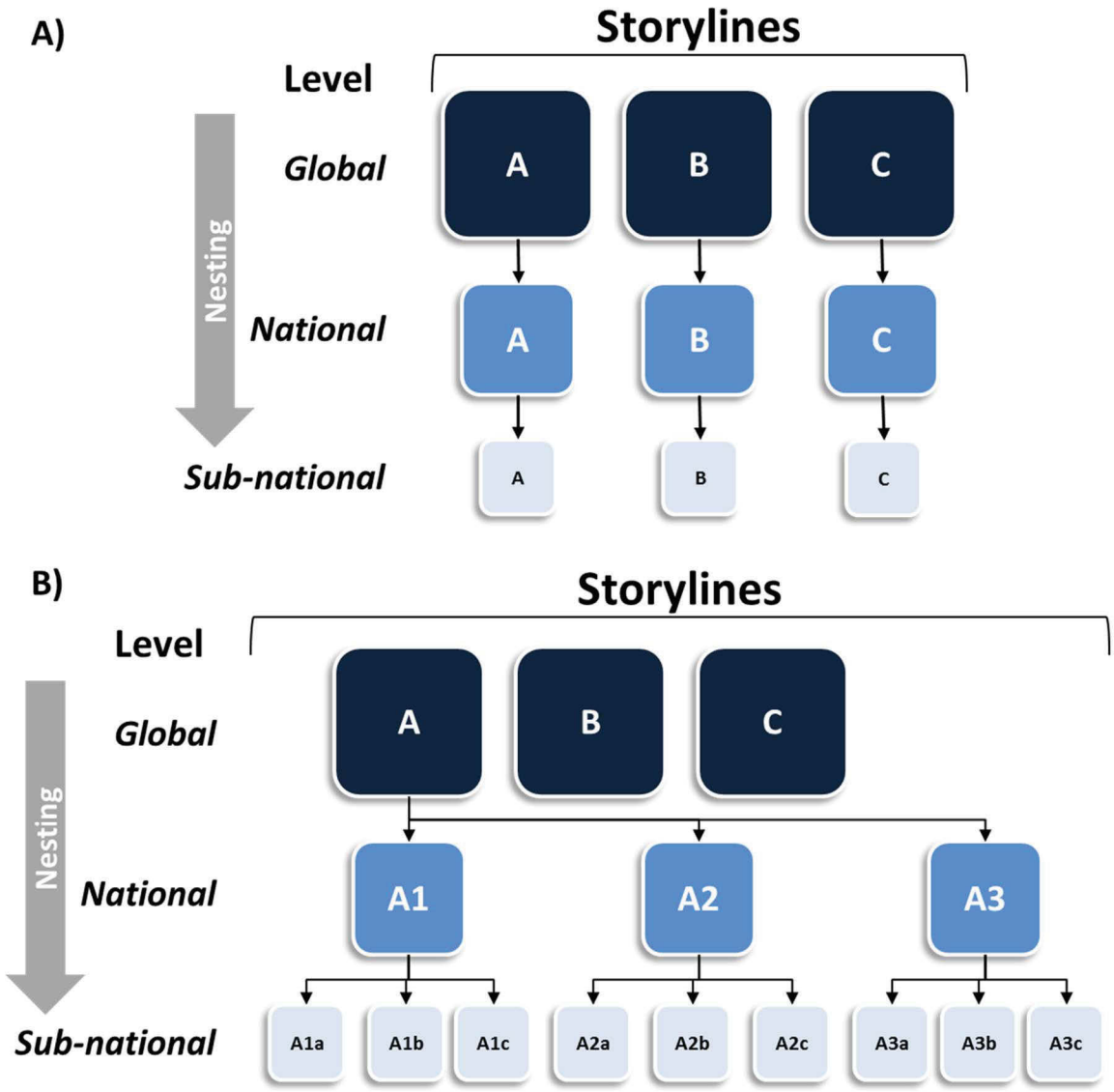

Figure 3. Comparison of alternative approaches to the development of nested socioeconomic storylines.

A) represents a one-to-one nesting approach, where each global storyline is consistent with a single storyline at sub-global scales. B) represents a one-to-many nesting approach, where each global storyline is consistent with a range of alternative storylines at other scales.

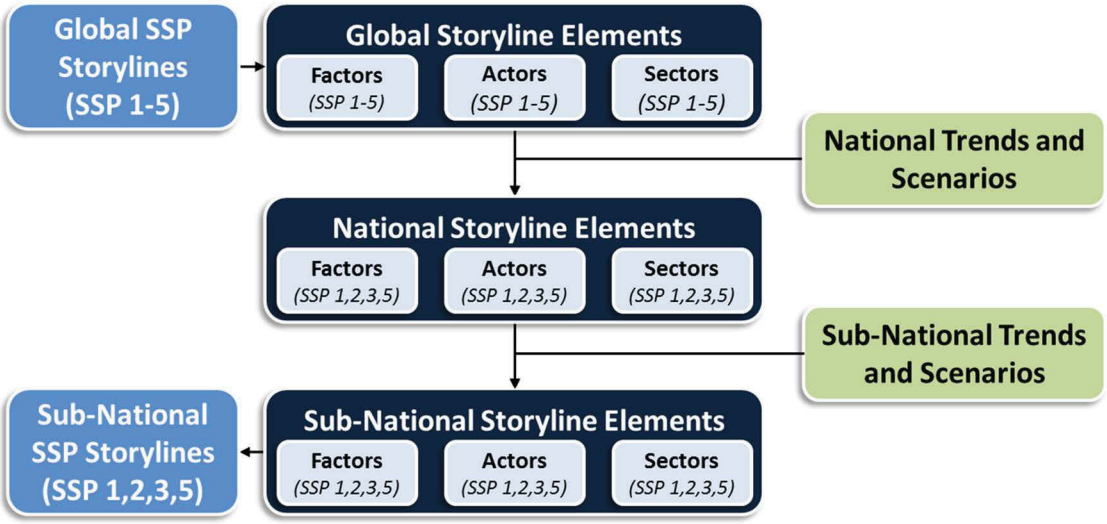

Figure 4. Illustration of SSP storyline nesting based on the Factors-Actor-Sector framework.

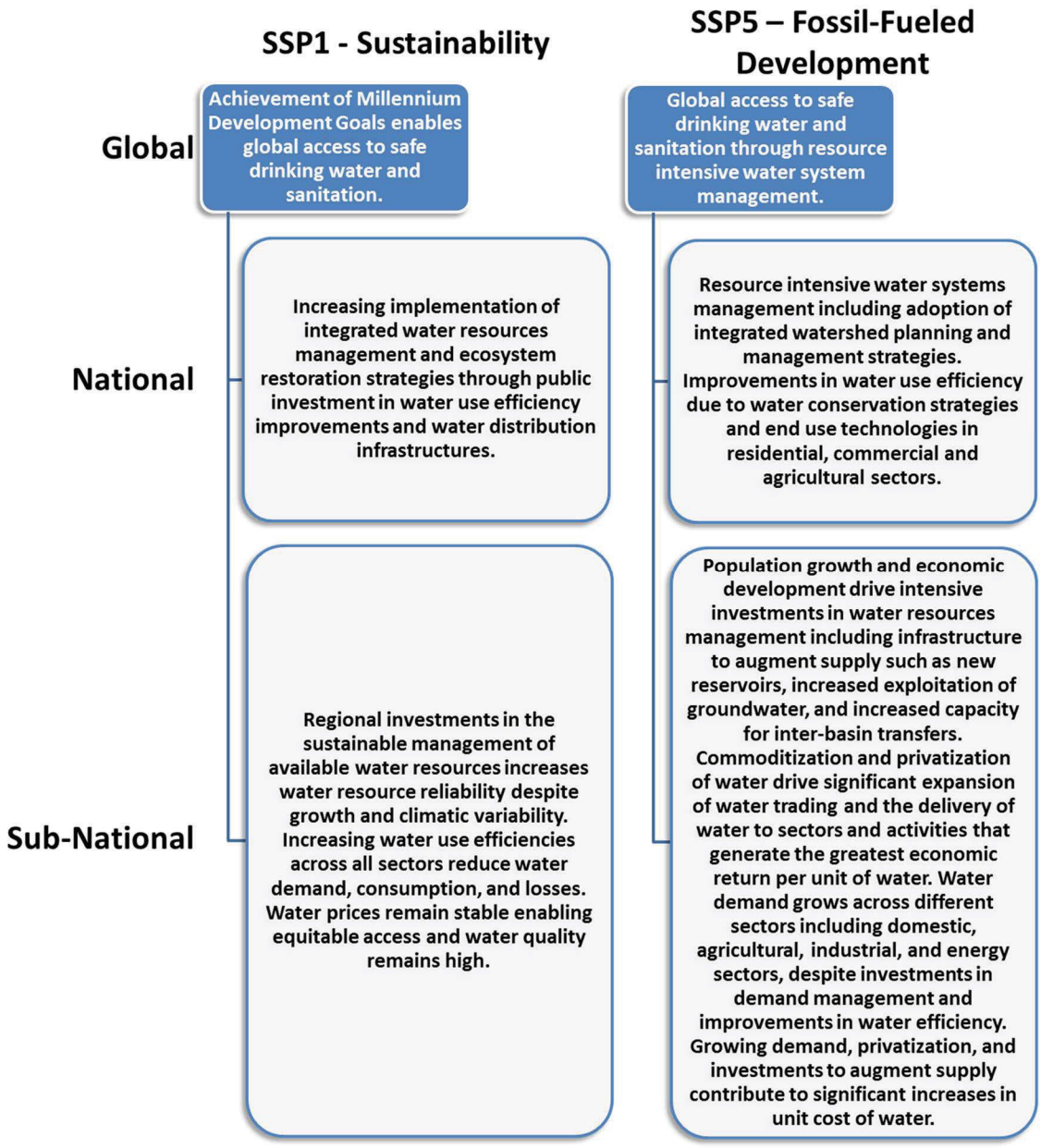

Figure 5. Comparison of the storyline elements for the water sector associated with SSP1 and SSP5 storylines.

The element description for the global level is based on the global SSP storylines. Elements at the national and sub-national level were derived through application of the Factor-Actor-Sector framework and were informed by other information sources on sectoral trends and scenarios (Table 1.2).

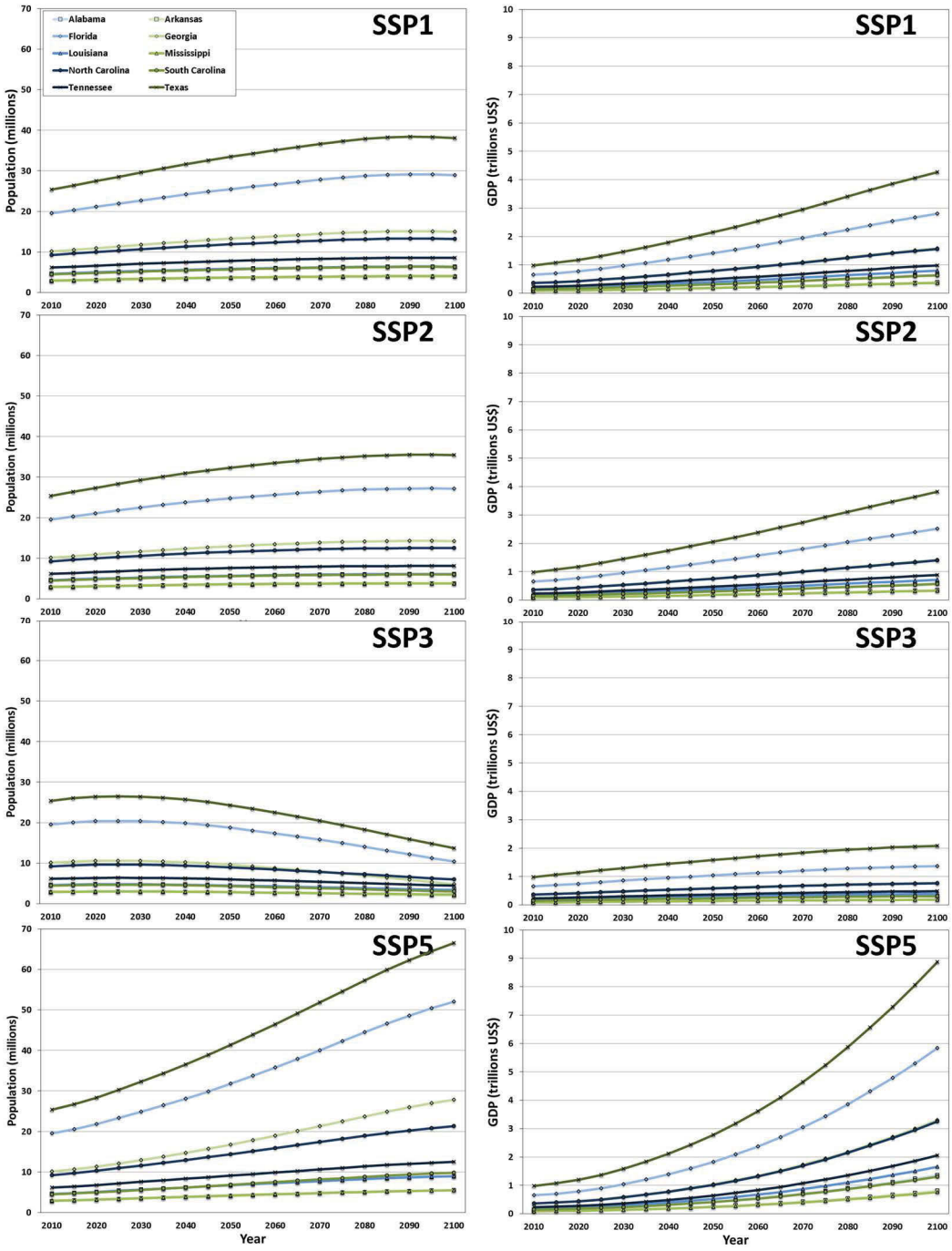

Figure 6. Quantitative population and GDP scenarios for states in the U.S. Southeast based on four different global SSP boundary conditions.

Population and GDP scenarios were derived by applying county-level scaling factors to national population and GDP estimates within the IIASA database (IIASA, 2012a). Population scaling factors were based on the proportion of total U.S. population change attributed to individual counties as indicated by the ICLUS population scenarios (2010-2100). GDP scaling factors were based on the historical (1997-2011) average proportion of U.S. GDP attributed to the states considered in the current study.

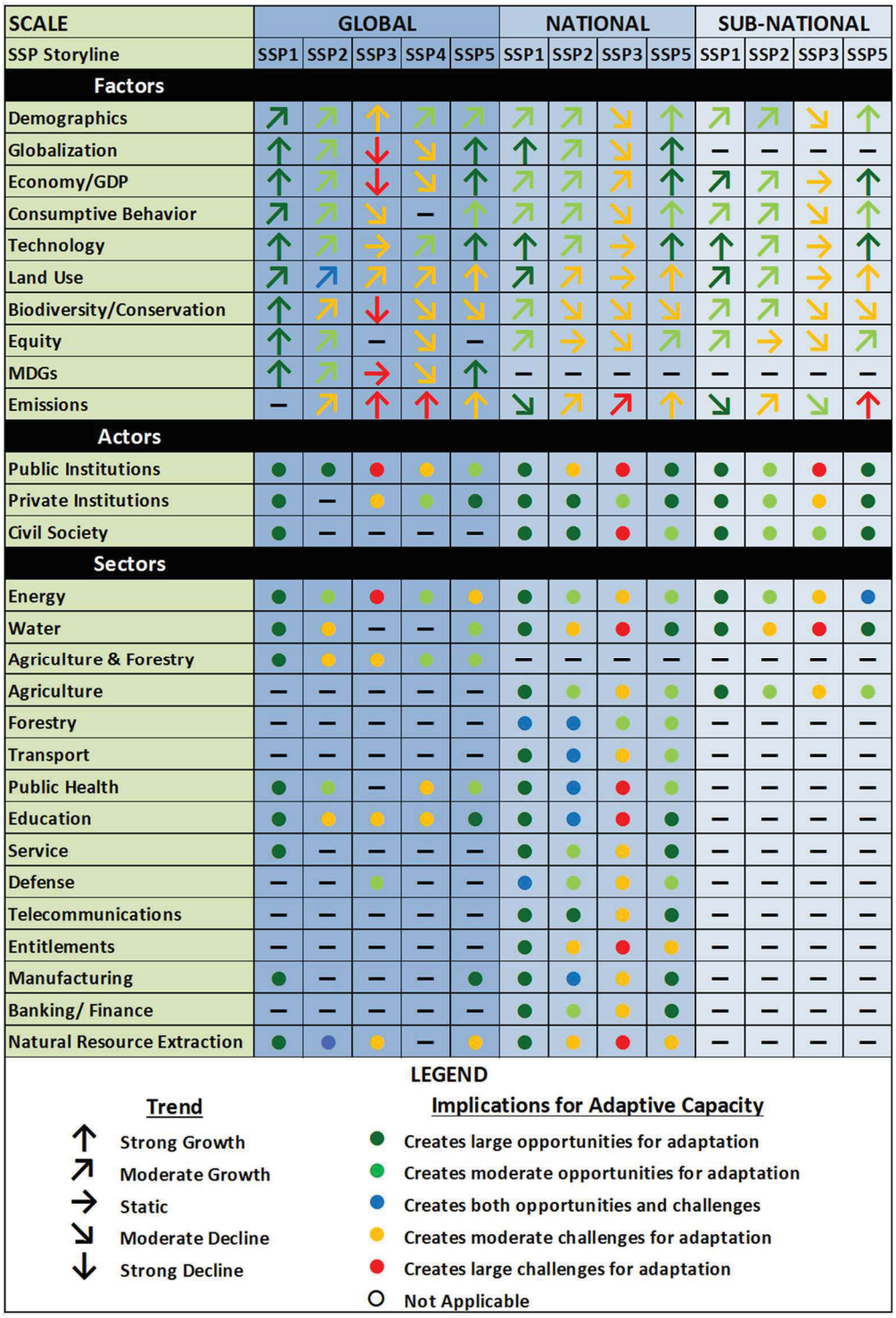

Figure 7. Synthesis of the status and projected trends of factors, actors, and sectors considered in the current study with respect to their implications for adaptive capacity across multiple scales.

Appendix 1.2 – Sub-National Storylines

Sub-national storylines for the U.S. Southeast region were developed based upon four of the basic global SSPs using the Factor-Actor-Sector framework described in Section 3.3. The sub-national storyline narratives were compiled from the underlying storyline elements and represent the culmination of the nesting approach applied in this study. The narratives themselves are presented below.

Sub-National SSP1 – *Sustainability*

The U.S. Gulf Coast region is characterized by high growth in GDP throughout the 21st century due to strong upward trends in population, urbanization and globalization. Growth in regional consumption is increasingly attributed to the use of low material- and energy-intensive products associated with sustainable supply chains and reduced environmental externalities. Civil society undergoes a transformational change toward consumptive behavior that emphasizes sustainable goods and services that capitalize on innovation and enterprises in the region. Large public and private investments in research and development allow the region to benefit from rapid innovation and technological advancements. Regional urbanization is focused on vertical development in existing urban centers and pan-urban areas including increased use of marginal and under-utilized land. Investments are made in ecosystem restoration and afforestation for carbon sequestration while expansion of biofuels leads to increased land use associated with biomass production. An increase in the skilled workforce increases per capita incomes and income equality while stronger social policies are adopted that help marginalized and disadvantaged populations. Greenhouse gas emissions are significantly reduced due to a shift away from fossil fuels toward greener and sustainable energy alternatives. These trends also lead to reduced energy demand and amelioration of the externalities of energy including reduced water consumption and improved air quality. Investments in the sustainable management of available water resources increase reliability despite climatic variability. Increasing water use efficiencies across all sectors reduce water demand, consumption, and losses. Water prices for consumers remain stable enabling equitable access, and water quality remains high. The region transitions toward sustainable agricultural systems that achieve higher yields and yield densities with fewer inputs. Local agricultural communities emerge that focus on the exploitation of primary agricultural products over meat and other energy/water intensive products. Local orientation of agriculture with self-sufficient enterprises helps keep food prices low.

Sub-National SSP2 – *Middle of the Road*

Gulf Coast states experience moderate rates of growth in GDP throughout the 21st century due to a rapid increase in population, employment, focus on alternative energy sources and efficient industrial processes. Increasing dependency on natural gas and alternative energy resources helps constrain

emissions to moderate to high levels. Stringent federal, state and local regulations around building codes and product standards enable efficiency gains, lower externalities of urban sprawl drive additional investments in renewable energy resources. The relatively low cost of living and high quality of life attracts people to the region, increasing both international and local migration. National and regional investments in technology research and development contribute to increasing regional efficiency and reduced carbon intensity of economic activity. Regional land use trends are dominated by high rates of urbanization with significant urban sprawl around existing urban centers. Environmental consciousness leads to retrofitting processes with greener alternatives, efficient low energy buildings, use of biofuels and modest ecosystem restorations. The region experiences continued disparity in income and wealth between skilled and unskilled workers and, particularly, between urban and rural populations. The private sector seeks to respond to market opportunities created by consumer demand while civil society continues to play an important role in driving the pace of economic growth and technological change through patterns of consumption and demand for goods and services. Energy demand is concentrated in residential and industrial sectors whereas energy supply is increasingly comprised of clean coal and natural gas facilities with modest gains in renewables such as wind, solar and biofuels. Increased demand, competition, and privatization of water resources drive up the water withdrawals, which are offset by incremental improvements in water supply infrastructure. Regional crop portfolios and crop management practices largely remain stable. However, the sector benefits from incremental improvements in yields and increased production efficiencies.

Sub-National SSP3 – *Regional Rivalry*

Gulf Coast states experience low rates of growth in GDP due to global economic headwinds that contribute to low levels of technological development, employment, resource use and consumption. Production largely depends on the competitive advantages among different U.S. regions and consumptive patterns are characterized by the use of local and regional sources derived from community-based production. Investments in research and development are highly constrained and thus technological innovation and change is limited to autonomous and incremental improvements of existing technologies. Due to slow efficiency improvements in processes, products and services, the region struggles to compete technologically with other U.S. regions. Land use change is modest due to limited growth and the continuation of existing settlement patterns. Additional land area is brought under cultivation to allow for growth in local farming and crop switching to enhance regional food self-sufficiency. Regional economic headwinds reduce resources and incentives for environmental conservation. Wealth is concentrated in a privileged few hands that disproportionately benefit from regional economic activity. Reduced industrial activity, slow economic growth and low fossil fuel consumption leads to low

emissions. State and local governments are weak and poorly resourced. Civil society is focused on identifying local solutions with minimal support from formal government institutions including self-organization to address key concerns of marginalized populations. Energy costs rise due to depreciation of existing infrastructure and limited opportunities to connect to national energy markets and inter-regional energy networks. Regional economic conditions preclude significant investments in water infrastructure whereas demand for water continues to increase modestly across sectors, in part due to lack of progress in demand management and efficiency improvements. The slow pace of national and regional economic development provides few incentives and little capacity for investments in agricultural research and development and thus long-term trends in yield improvements and increased efficiencies plateau. Surplus crop production is increasingly traded within the region to meet the demand for food.

Sub-National SSP5 – *Fossil-fueled Development*

The U.S. Southeast economy expands at an exponential rate over the 21st century due to Fossil-fueled Development in population, urbanization, resource use and technological development leading to higher levels of production and consumption of goods and services. Regional consumption increases rapidly with an emphasis on maintaining low cost products by the efficient exploitation of available resources. Technological innovation is used to offset the externalities associated with intensification of consumption, increasing resource use, and urban sprawl. High rates of population growth and urbanization drive rapid land use conversion and increased pressure on public and private agricultural and forested lands that are not protected, thus contributing to degradation of biodiversity, reduced ecosystem resilience, and increased greenhouse gas emissions. Government institutions prioritize maximization of economic development including policies to incentivize business development and extra-regional trade. The private sector leads investments in research and development, human capital, and infrastructure in order to maximize economic gains and to meet the need for efficient, robust, and resilient infrastructure systems to enable commerce. Civil society provides a leading voice for environmental conscientiousness and greening of conventional energy processes as a counter to government and the private sector, which focus on maximization of economic growth. Energy demand increases due to rapid population growth and economic development with the supply largely dependent on coal, oil and natural gas as technological advances enable increased exploitation of non-conventional fossil fuel resources. Population growth and economic development drive intensive investments in water resources management including infrastructure to augment supply and water markets to drive water consumption to its most productive use. Population growth and fluid trade increase demand for agricultural land resulting in greater tensions between urban/rural land use. The agricultural sector concentrates on maximizing

production of traditional stable crops, with the growing demand for high value crops met through imports.

Chapter Two - The Tradeoff Between Water And Carbon Footprints Of Barnett Shale Gas

A version of this chapter was originally submitted to the Journal of Cleaner Production by Syeda Mariya Absar, Anne-Marie Boulay, Maria F. Campa, Benjamin L. Preston, and Adam Taylor:

Absar, S. M., Boulay, A.-M., Campa, M. F., Preston, B. L., Taylor, A. (2017). The Tradeoff between water and carbon footprints of Barnett shale gas. Journal of Cleaner Production (In review). The authors are awaiting a decision from the journal.

The article is presented in its original form, formatted for this dissertation including renumbering tables and figures. Author was lead author and lead investigator on study. Coauthor Anne-Marie Boulay helped augment the analysis with her expertise in water scarcity footprint calculation, Maria F. Campa helped collect the data for the life cycle assessment, coauthor Benjamin L. Preston supervised the development of this work and provided critical revisions for important intellectual content, and coauthor Adam Taylor helped in data interpretation and manuscript evaluation.

Abstract

Shale gas production is a water and energy-intensive process that has expanded rapidly in the United States in recent years. This study compared the life cycle water consumption and greenhouse gas (GHG) emissions from hydraulic fracturing in the Barnett region of Texas, located in one of the most drought prone regions of the United States. Four wastewater treatment scenarios were compared for produced water management in the Barnett region. For each scenario, the cradle-to-gate life cycle global warming potential (GWP) and water scarcity footprint (WSF) was estimated per mega joule of gas produced. The results show a trade-off between water and carbon impacts, because energy is required for treatment of water. A reduction of 49 percent in total water consumed or a 28 percent reduction in the WSF in the shale gas production process can be achieved at a cost of a 38 percent increase in GWP, if the wastewater management shifted from business as usual to complete desalination and reuse of produced water. The results are discussed in the context of wastewater management options available in Texas.

Introduction

Energy is required to provide water, and water is often required to provide energy. Currently 15 percent of the total world water withdrawals are used for energy practices, out of which 11 percent is consumed during energy production. By 2035, water withdrawals are predicted to increase by 20 percent and water consumed during energy production is predicted to increase by 85 percent. These trends are due to a shift towards higher efficiency power plants with more advanced cooling systems that reduce withdrawals, but increase consumption

per unit of electricity produced, and by the expansion of biofuels production (IEA, 2012).

Variability in water resources due to extreme temperatures and uncertain precipitation conditions is anticipated for most regions of the United States in the future (Roy et al., 2012), increasing the importance of accounting for water use in energy production. As water-intensive energy technologies become more widespread, water treatment and/or reuse may help to reduce the strain on water resources. However, handling and treating wastewater is an energy-intensive process. Hydraulic fracturing (fracking) is an example of the type of water-intensive energy technology that has grown rapidly in recent years. Fracking is the process of injecting pressurized water and chemicals in a subterraneous rock (i.e. shale) to create fractures that release natural gas or oil to the surface (EPA, 2015). A single fracking well in the Barnett shale of Texas is estimated to require an average of 15 million liters of water over its lifetime, and at the current rate, 10 to 70 percent of that will be discharged as wastewater (Clark et al., 2011; Mantell, 2011).

Because of the rapid growth in fracking, efforts have been made to apply Life Cycle Assessment (LCA) to enhance understanding of the environmental implications of this technology. Two key indicators evaluated in such assessments are the greenhouse gas emissions (GHG) and the water scarcity footprint (WSF) of the shale gas production process. With regard to water consumption, prior analyses have largely focused on the Marcellus shale in Pennsylvania (Jiang et al., 2014, 2011; Laurenzi and Jersey, 2013). Although Grubert et al. (2012) have quantified the freshwater consumption for the entire natural gas extraction process in Texas, they only report the estimated cradle to gate values for water consumption per shale play based on their estimated ultimate recovery. This paper highlights how much water is consumed at every life stage of shale gas extraction process, from cradle to gate in a single well, with respect to water scarcity in the watershed, for four disparate wastewater management scenarios.

In this study, we estimated the global warming potential of Barnett shale gas production from fracking and the water scarcity footprint based on the inventory of water, energy and materials consumed to produce a mega joule of shale gas, from a well's construction to its closure. This 'cradle to gate' study is based on the format developed by Jiang et al. (2011, 2013), but we defined and compared a range of wastewater management scenarios in order to understand the impact of wastewater management option used on the overall carbon and water scarcity footprint of shale gas production, given the current state of technology in the Barnett shale play. We apply a consensus-based midpoint water scarcity method, consistent with the ISO 14046 standard, to determine the water scarcity footprint and the associated water deprivation potential (Boulay et al., 2017).

Water degradation and quality aspects of use in shale gas production are outside the scope of this study.

Background

Hydraulic fracturing is an unconventional gas extraction method, as the hydraulic technique is coupled with horizontal drilling instead of the conventional vertical drilling method. This “unconventional” technology has greatly increased the extraction of “tight” oil and shale gas, helping the U.S. become the world's top producer of petroleum and natural gas hydrocarbons in 2014 (Laurenzi and Jersey, 2013). Texas is the largest conventional and unconventional gas producer in the United States as of 2013 (Jiang et al., 2011). Since 2008, more than 17,000 oil and gas wells have been drilled in the Barnett Shale (Jiang et al., 2014) and another 14,000 are predicted by 2030 (Grubert et al., 2012). As a consequence, fracking is becoming a major component of water withdrawals in Texas. Compared to all county water consumption in 2008, water consumption for shale-gas production at the county level for Barnett shale play was projected to increase from 1 percent to 40 percent when the gas production peaked (Boulay et al., 2017).

The Barnett shale is a hydrocarbon producing, geological system that is a part of the Bend Arch–Fort Worth Basin, located in north central Texas and southwestern Oklahoma. Major portions of its fields are part of the Dallas-Fortworth Metroplex urban area, underlying the cities of Dallas, Fortworth and Arlington in north central Texas. The Barnett shale play was the first in the United States (U.S.) to have shale gas extracted by hydraulic fracturing in 1983 (Wood et al., 2011). In 2013, Texas was the largest shale gas producing state in the U.S. (Tran, 2014) with the Barnett shale producing 20 percent of the total U.S. shale gas (Nicot et al., 2014). Barnett shale is a high “long term produced water” generating play, which means that due to the presence of water in and around the shale, on average it generates more than 134 cubic feet (<1000 gallons or $<3x10^3$ liters) of water per million cubic feet (~1 MJ) of shale gas produced. This water is not accessible via groundwater pumping because these formations are located deep underground and can only be accessed via fracking (Mantell, 2011). This shale play produces approximately $1.8x10^6$ to $2.3\ x10^6$ liters of water per well in the first 10 days after completion. This is by far the largest volume of produced water from any major shale play. This water is sufficient to provide approximately 10-15 percent of the total water needed to fracture a new well. Large volumes generated within a short period of time make reuse of produced water feasible (Mantell, 2011). For the sake of simplicity, the term *produced water* is used as a collective term for all water that is returned to the surface through a well borehole and is made up of water injected during the drilling process (drilling wastewater), fracture stimulation (flowback water) and gas production (produced water), as well as the natural “formation” water (Jiang et al., 2014).

Barnett shale produced water generally has high levels of total dissolved solids, low total suspended solids and moderate scaling tendency, which makes it suitable for blending with freshwater and filtration for reuse. However, the Barnett shale utilizes Class II (salt water disposal) underground injection control wells as permitted by the Environmental Protection Agency (EPA, 2016). In some cases the disposal wells are old oil and gas wells from which fuel has been extracted. In others, they are enhanced recovery wells wherein fluids are injected to maintain pressure in an oil field that has been depleted by oil production, and also to recover residual oil (EPA, 2016). In Texas, there were over 11,000 Class II disposal wells in 2008, or slightly more than one disposal well per gas producing well in the Barnett shale (Gregory et al., 2011). These wells provide a more economical and low energy alternative to advanced reuse (Mantell, 2011), but at the cost of large volumes of water consumed and not available for other uses within an already stressed watershed (Bené et al., 2007).

In the Barnett shale, only 5 percent of water for drilling and fracking is sourced from reused or recycled water. The rest of the water is sourced equally from fresh ground water wells and from surface water (EPA, 2015). In contrast, for fracking in the Marcellus shale in the Susquehanna River basin, approximately 60 percent of water is sourced from surface water and 60 – 90 percent of the produced water is reused (EPA, 2015). Because the percentage of reuse is very low in the Barnett, most of the produced water is disposed of by deep well injection (Nicot et al., 2014; EPA, 2015). As the metropolitan area of Dallas-Fort Worth expands, the growing population's water demand and the water demand of the gas industry will compete in what is already a water scarce area. According to water budget predictions, the aquifers may no longer be able to sustain the pressing water demands by the year 2025 (Bené et al., 2007). Thus, there may be long term benefits to recycling and reusing the produced water in the Barnett.

Methods

The LCA was conducted using the SimaPro Life Cycle Analysis version 8.2.0 software (PRé-sustainability, 2014), and the well operation, hydraulic fracturing and water management parameters were obtained from various sources (Tables S1 & S2). Data for upstream processes were adopted from the USLCI & Ecoinvent databases. The input processes used were 'market processes', which include inputs from production in several countries as well as inputs of transport processes. When the specific supplier or the origin of a product is not known, it is recommended to use the market processes (Ponsioen, 2013). The inventory for steel inputs for well preparation were acquired from the USLCI database, however the upstream water data was taken from a position paper published by the World Steel Association (World Steel Association, 2015). As for all other chemical inputs, the estimates of quantities are taken as the average value of a

range of values provided in the literature (McCurdy, 2011; Stringfellow et al., 2014) for unconventional shale gas production or as exact values published specifically for Barnett shale (Clark et al., 2011). Currently, the Texas electricity grid is sourced from a mixed resource portfolio with the highest amount of electricity generated from coal and natural gas and roughly 9 percent from wind (EIA, 2016). This energy mix was modeled using Ecoinvent 2.0 for all energy inputs from the grid for this study. The available databases also do not provide specific information on the type of cooling system a power plant uses, which makes it difficult to quantify water consumption (Berger and Finkbeiner, 2010) which is why water for cooling and turbine use was excluded from the inventory water consumption calculations.

Shale gas production process

We developed a shale gas production process in the SimaPro LCA software package (PRé-sustainability, 2014), which links the types and quantities of the various inputs and emissions to relevant upstream process data contained in the U.S. Life Cycle Inventory Database (National Renewable Energy Laboratory, 2012) and the Ecoinvent v3 (Weidema et al., 2013) databases. These databases provide data for energy and material flows associated with producing a material, component, or assembly. The shale gas production process comprises the following sub processes: drilling and construction of the well, hydraulic fracturing, well completion, and gas production (Figure 8).

Life Cycle Assessment Approach

The goal of LCA was to understand the GHG emissions and water consumption associated with shale gas production in the Barnett shale of Texas, under different wastewater management scenarios. In our study, Barnett shale natural gas is the fuel produced and water is consumed as part of the shale gas production process. The reference flow for this study was one mega joule (MJ; higher heating value) of gas produced from typical shale wells. The impact categories used to quantify the GHG emissions and water consumption from this process are the *global warming potential* expressed as kilograms of carbon dioxide equivalent per mega joule of natural gas produced (kgCO2eq/MJ), and the *water scarcity footprint* reported in liters world equivalent per mega joule of gas (L world eq/MJ) respectively.

Our analysis is 'cradle-to-gate:' the boundary of our shale gas production process includes well pad preparation, drilling, well completion and gas production but does not include transportation and combustion of the gas (Figure 8). Each of the inputs to this process had associated "upstream[1]" inputs and emissions, which were included in this assessment. The sources of GHG emissions considered in this LCA included: emissions from the production and transportation of materials

[1] Upstream processes provide the materials and energy inputs to the process under consideration. These generally occur off-site but their environmental impacts are attributed to the process.

involved in the well development activities (such as trucking water); emissions from fuel consumption for powering the drilling and fracturing equipment; methane leaks and fuel combustion emissions associated with gas production. Water use was assessed from well pad preparation, well drilling and construction, hydraulic fracturing and the production of shale gas. Well site investigation and preparation were assumed to have negligible water impacts and GHG emissions; hence they were excluded from analysis.

After construction of the well pad and its access roads, wells are drilled vertically and then horizontally; drilling fluids are used, and drilling wastewater is generated. Well pads normally support multiple wells, usually a range of 1-16 (Jiang et al., 2014), however, we assumed 6 in this analysis (Wood et al., 2011). Hydraulic fracturing takes place after well drilling and uses a mixture of water, sand, and frac chemicals that make up the hydraulic fracturing fluid. Table 2.3 summarizes the inputs and outputs for each sub-process considered in this LCA, their estimation approaches and their data sources. Fracking waste fluid comes from the well as "flowback" water. Trucks are the predominant method to transport water to the well site, and truck transportation was also assumed for wastewater management in the study. Later, trucks are used to transport (non-recycled) wastewater from the well site to treatment or disposal locations. Typical Barnett shale wells produce 35 million cubic meters of natural gas (Howarth et al., 2011) over its life-time, which can range up to 30 years (Clark et al., 2011). Once a shale well no longer produces at an economic rate, the wellhead is removed, the wellbore is filled with cement to prevent leakage of gas (Clark et al., 2012). The potential impacts of shale gas production on the geology and seismic activity were outside the scope of this study.

Life Cycle Impact Categories

(1) Water Scarcity Footprint (WSF)

The LCA impact category for water consumption is water scarcity. Water scarcity footprint is an indicator that addresses potential impacts associated with the quantity aspect of water consumption without considering the additional quality component of availability. A consensus-based method called Available WAter REmaining (AWARE) is used to calculate the WSF as a water use midpoint indicator (Boulay et al., 2017). AWARE is calculated on a per area basis in a watershed, after the demands of humans and aquatic ecosystems have been met. AWARE is in compliance with the international standard for water footprint, ISO 14046 (International Organization for Standardization, 2014) and makes comparison across studies possible. It assesses the potential for water deprivation, to either humans or ecosystems, building on the assumption that the less the water remaining available per area, the more likely that another user will be deprived, calculated in liters world equivalents per mega joules of shale gas produced (Boulay et al., 2017).

To calculate the WSF, first the total water consumption of the process was calculated, in liters of water per mega joule of shale gas (L/MJ), by aggregating the water consumed in the same watershed. There are two types of water consumptions considered for calculating the total water consumed, *direct water consumption* and *indirect water consumption*. The *direct water* consumption occurs at the well site mainly for well drilling and hydraulic fracturing and the *indirect water* is consumed during the well drilling and hydraulic fracturing activities, as part of their upstream processes in producing drilling mud, fracturing proppant, chemical additives and all other material and energy inputs.

Direct water is considered to be consumed when it is not returned to the same watershed in the form of produced water, which can be readily used by other users (humans or ecosystems). Produced water is considered to be consumed when it is injected into deep underground wells as a means of wastewater management. However, if the produced water is desalinated or treated for reuse purposes, it is not considered to be consumed. In our study we assumed desalination using reverse osmosis and water treatment in a traditional municipal facility as the preferred methods for water treatment. The indirect water consumption in shale gas production process was calculated using the inventory data in SimaPro version 8.2.0. Water consumed during hydroelectric generation or for cooling in power plants was not considered to be consumed (Berger and Finkbeiner, 2010; Pfister et al., 2009; Pfister, 2011; Hoekstra et al., 2011; Flury et al., 2012).

The total inventory of water consumption in shale gas production was calculated separately for direct and indirect water consumption using the following equations, adapted from Grubert et al. (2012):

Direct W_C = Total input (drilling + fracturing) water consumed (L/MJ) + total produced water consumed (L/MJ) (Eq.1)

Indirect W_C = Water embedded in proppant (L/MJ) + water consumed in producing chemicals (L/MJ) + water consumed in producing all other inputs including energy (L/MJ) (Eq.2)

Once the direct and indirect water consumption (Direct W_C and Indirect W_C) were calculated for the system, they were multiplied with their respective location or region specific characterization factors, CF_{AWARE} (based on the inverse of available water remaining per unit of surface and time in a region or watershed), to calculate the water scarcity footprint or the potential to deprive another user of water (Boulay et al., 2017). Therefore, the Water Scarcity Footprint of shale gas production was calculated according to equation 3:

WSF_{TOTAL} = (Direct area weighted WC x Barnett shale watershed CF_{AWARE}) +

(Indirect WC x USA CF_{AWARE}) (Eq.3)

The WSF for the direct water use was calculated using the sub-watershed level CFAWARE values for non-agricultural use, aggregated to the annual resolution available through WULCA, Water Use in LCA Working Group (Boulay et al., 2017; WULCA, 2017). As the Barnett shale play is located in two watersheds (with CF values 1.27 and 4.72 respectively), an area-weighted average was used to determine the most accurate estimation of CF_{AWARE}. The exact area within each watershed was based on the USGS National Assessment of Oil and Gas Project for Barnett Shale (USGS, 2016). The consumption of indirect water takes place in different watersheds within the U.S., especially for the upstream processes for steel, cement and sand, which have significant contributions to upstream water consumption (see Figure 11). These inputs are assumed to be manufactured entirely within the United States. According to the Portland Cement Association (2016), Texas produces 10 metric tons of cement annually and is the leading cement producing state in the US (Stephen M. Jasinski, 2017). The U.S. produces 75 percent of steel to meet domestic consumption (USGS, 2015) with several manufacturing facilities producing steel pipe and tube casings for the oil and gas industry in Texas (United States Steel Corporation, 2015). The sand used as a proppant in fracking is sourced from within Texas (Nicot and Scanlon, 2012) as two of the major silica sand producing states in the U.S. are Wisconsin and Texas (Dolley, 2016). Similarly, most of the fracking fluid is also produced by a few key market players such as Baker Hughes, Chevron Phillips Chemical, Schlumberger and Halliburton, and also have the largest market share of fracking fluid manufacturing in the U.S. as most of these companies have hands on experience with hydraulic fracturing (Grand View Research Corporation, 2017). Therefore, the country level annual average CFAWARE value for non-agricultural use in the United States (CF value = 9.5) was used to calculate the water scarcity footprint of the indirect water consumed (Boulay et al., 2017). The final water scarcity footprint, calculated for each of the four scenarios (section 4.2), was the sum of the direct and indirect water scarcity footprints (Table 2.5).

(2) Global Warming Potential (GWP)

Global warming potential (GWP) is an indicator of the combined contribution of GHG emissions to climate change (Bare, 2011). Each process in the shale gas life cycle has an associated upstream supply chain that was included in this study by means of life cycle inventory available in SimaPro. The sources of GHG emissions considered in the LCA include emissions from the production of materials; fuel consumption for powering the drilling, fracturing, gas production and transportation equipment; and methane leaks. The *Tool for the Reduction and Assessment of Chemical and other environmental Impacts* (TRACI v2.1) model (Bare, 2011) was used to calculate GWP based on characterization factors that quantify the relative impacts of various gases (e.g. CO_2 and

methane) in terms of CO_2 equivalents per unit of shale gas energy produced (kg CO_2 eq/MJ).

"Fugitive" methane emissions occur when the gas is lost to the atmosphere during the production process. Fugitive emissions from shale gas production process are at least 30 percent more than those from conventional natural gas production (Howarth et al., 2011) and methane is a potent GHG (Hultman et al., 2011). At the beginning of shale gas production, large volumes of water are injected to fracture the rock formations. "Flowback" of water, mixed with methane and other hydrocarbons, occurs over subsequent days or weeks. More methane is emitted during the drilling process, when the plugs installed to separate fracturing stages are drilled out to release gas for production. Fugitive methane volumes emitted during flowback and drilling were estimated to be 1.1 and 0.3 percent, respectively, of the total life-time production of shale gas from a Barnett well (Howarth et al., 2011), of which only 15 percent is flared (EPA, 2011; Skone et al., 2011).

A typical shale well requires roughly 1 million liters (270,000 gallons) of freshwater for drilling and well construction (Werline, 2011). Over a 30-year life cycle (Clark et al., 2011), a typical well is hydraulically fractured three times (Clark et al., 2012). A single fracturing job requires 18,000 liters (4771 gallons) of diesel (Clark et al., 2011). In order to procure the input water from surface or ground water sources, roughly 11,000 liters (3,000 gallons) of diesel (Clark et al., 2011) and about 186,000 kwh of electric energy is required (Goldstein and Smith, 2002; EPA, 2013) for transportation and municipal wastewater treatment. For the management of the produced water, approximately 20,000 liters (5,400 gallons) of diesel is required to transport the water to and from treatment facilities or disposal wells (Clark et al., 2011).

Barnet shale water production and management

After fracturing a well in Barnett, anywhere from 15 to 20 percent of the original volume of the fluid will return to the surface within the first 10 days as flowback water (Mantell, 2011). On average 1.1 million liters of water is produced per fracturing job in the Barnett shale (Clark et al., 2011). Additional water, equivalent to anywhere from 10 percent to almost 300 percent of the injected volume returns to the surface as produced water over the life of the well (Clark et al., 2012). While most other plays do not recover all of the hydraulic fracturing fluid during the flowback period, the Barnett shale typically yields a larger volume of flowback water (composed primarily of natural formation water), than was used during hydraulic fracturing activities (Clark et al., 2011).

Treatment and Disposal Options for Produced Water

Underground injection is the most common disposal method for produced water from Barnett shale wells. This option is legal and inexpensive due to the presence of an extensive network of Class II disposal wells (Mantell, 2011). Barnett shale produced water generally has high levels of TDS (500 – 200,000 mg/L). One of the recommended technologies for produced water treatment by the Environmental Protection Agency (EPA) is reverse osmosis (Alleman, 2011), which is an energy intensive process (Hayes, 2011; Mantell, 2011). The Barnett area is not yet equipped with desalination plants that have the capacity and technology to deal with the pretreatment requirement of flowback water. However, multiple companies piloting reverse osmosis desalination plants, aimed at treating flowback water, are currently operational in the area (Alleman, 2011; Hayes, 2011). This technology is 70 percent more energy efficient than other desalination technologies (Al-Karaghouli and Kazmerski, 2012) and is able to handle high salt content. The Barnett shale play produces significant volumes of initial produced water, which could enable reuse; however, this potential is limited by storage, transportation and other economic factors (Mantell, 2011).

Scenarios Evaluated

In this study, four scenarios were evaluated based on different wastewater management options for Barnett shale wells. For a given scenario, the drilling and hydraulic fracturing stages of the shale gas extraction process remain the same, however, the choice of wastewater management option determines the differences in the overall carbon and water footprint of the shale gas production process. These scenarios differ in terms of energy and water use intensity, as well as the sources of water. For instance, in scenario 3 and scenario 4, water from desalination is re-used as input water. The input percentages from surface and groundwater are determined after all the available desalinated water is used to meet part of the input water requirements (Table 2.2). The number of trucks, the diesel used for transporting water from well site to disposal treatment site, and the distances traveled, in each scenario, were calculated specifically for Barnett shale wells (Clark et al., 2011) and are listed in Table 2.4. The energy requirements for municipal wastewater treatment, the energy requirements for desalination, and the average distance from well site to desalination plant are also listed in Table 2.4, Supplementary data. The wastewater management scenarios are explained in Table 2.1.

Results

Complete underground injection (Scenario 2) has the highest inventory water consumption and WSF per unit of shale gas produced (Figure 9). *Complete desalination and reuse* (Scenario 4) has the lowest inventory water consumption and WSF but the highest GWP, due to the additional energy inputs required for transporting and treating the produced water. The scenarios that use more energy intensive processes such as desalination have a higher GWP per unit of

gas produced but with the trade-off effect of reducing the water consumption of the produced gas; a shift from *Business as usual* (scenario 1) to *Complete desalination and reuse* (scenario 4), increases the WFP by 38 percent, reduces inventory water consumption by 49 percent, and reduces the WSF by 28 percent (Figure 10).

The Water Scarcity Footprint

The resulting WSF, using the Boulay et al. (2017) AWARE method for shale gas production in Barnett, reveals a user deprivation potential of 2.60×10^8 liters world equivalents for the *Business as usual* and the *Complete injection* scenarios. The scenario with *complete desalination* has the lowest overall WSF of 1.88×10^8 liters world equivalents albeit at the expense of much higher GWP as compared with all other scenarios (Figure 10). The inventory water consumption and the water scarcity footprints for the direct and indirect water use, for each of the four scenarios are shown in Table 2.5. The indirect WSF is higher than the direct WSF because the characterization factor, CF_{AWARE}, for indirect water consumption (9.5) is much higher than those for both watersheds (CF values 1.27 and 4.72) where direct water consumption took place.

Each sub-category of inputs to the shale gas production process has a global warming potential and water scarcity footprint (Figure 10). The WSF bars are highlighted with diagonal lines to make the comparison across the scenarios more visible and also to separate them from the GWP bars. The GWP bars show both upstream and on-site inputs combined, where as, the upstream (indirect water) and on-site (direct water) is calculated and shown separately in the WSF bars. The WSF associated with diesel fuel is negligible which is why it is not visible on the scale shown in Figure 10.

This analysis identifies the hotspots - the process components with the highest impacts in terms of global warming potential and water scarcity footprint, both upstream and on-site. Steel production is the highest contributor to global warming potential and water scarcity footprint in the entire shale gas extraction process. Cement has the second highest GWP whereas sand has the second highest WSF (Figure 11). Steel and cement are used to create the well pad, line the wells after they are drilled, and sand is used as a proppant in the hydraulic fracturing process. Sand is often mined from natural sand deposits and requires more water than typical aggregate plants because of the grain-size sorting involved. Overall, these two additional water uses (drilling and sand mining) amount to an additional ~25% of water consumption relative to water consumed solely for fracking (Nicot and Scanlon, 2012). Soda ash and activated bentonite are inputs to the drilling fluid (Clark et al., 2011), while the rest of the chemicals shown in Figure 11 make up the hydraulic fracturing fluid (McCurdy, 2011; Stringfellow et al., 2014) (see Table 2.3 for details).

Discussion

The Barnett shale play has an extensive disposal infrastructure that allows operators to inexpensively dispose of flowback and produced water, thus developing and implementing a cost-competitive sustainable water management program using recycling is challenging (Werline, 2011). Deep well injection of produced water requires relatively little energy for transportation and injection of the water into disposal wells (Mantell, 2011). By contrast, the energy requirements to treat Barnett shale produced water are significant, particularly if advanced technologies are used. Because most energy sources result in GHG emissions, water use, and/or waste generation; reusing produced water may have greater environmental impacts. Reuse also requires water storage facilities and a proper means of disposing of the concentrated waste that results from treatment of produced water. There is a great degree of uncertainty about future development and technology use surrounding shale gas production in Texas, hence the use of alternate socioeconomic scenarios, highlighting disparate development trends and the underlying state of water and energy sectors, may be a useful tool to explore implications of different water management options.

A decision to adopt a *complete desalination and reuse* management option could be a trade-off of higher global warming potential for lower water scarcity footprint of shale gas production. The potential benefit of this trade-off would depend on whether water conservation is seen as more important than GHG emissions. The increased energy inputs associated with this tradeoff (e.g. diesel fuel to transport water or electrical energy to power desalination) also imply a higher cost for the gas produced. If the cost of desalinating 1 acre foot (1,300,000 liters) costs between $800 to $1,400 (TWDB, 2007), this would equate to an extra $21,000 to $37,000 in water treatment costs for the average well (not including infrastructure and transportation costs). These costs are small on a per-MJ of gas basis (<0.03 cents) but could be important to producers. Policy makers would therefore be faced with tradeoffs of water, energy and cost when considering water disposal options for fracking operations.

The WSF of shale gas was used as a metric to assess the potential deprivation of humans or ecosystems, based on the relative available water remaining per area in a watershed. The resulting WSF varies between watersheds within the Barnett shale play, and as compared with the entire U.S. and also across the four scenarios used. The two watersheds evaluated within the Barnett shale have different characterization factors and area weighted consumption, resulting in one area expressing a higher WSF than the other. Similarly, when the direct WSF (watershed based) is compared with that of indirect water scarcity footprint (U.S. country level based), the indirect WSF is higher than the combined direct WSF because the characterization factor for indirect water consumption is much higher than those for both watersheds where direct water consumption took place. When comparing the potential deprivation of the water consumption for the

four scenarios, the WSF for the *business as usual* and the *complete underground injection* is the highest, with observed reductions in the *partial desalination and partial injection* scenario. The scenario with *complete desalination* has the lowest overall WSF albeit at the expense of much higher GWP as compared with all other scenarios.

LCA practitioners agree that the available databases such as Ecoinvent and Gabi still lack information on types of water sources, spatial information and water quality data. In addition, large inconsistencies exist between databases with respect to water use and water consumption in products and processes (Berger and Finkbeiner, 2010; Pfister, 2011). The value of this study is that it uses a consensus-based water scarcity footprint indicator, which is in compliance with the international standard for water footprint, ISO 14046 (International Organization for Standardization, 2014) and makes comparison across studies possible. This study also provides a basis for comparing water disposal options using impact categories currently being used in the industry to understand the drivers of water and energy use in shale gas production in Texas.

This potential trade-off of GWP for water savings in shale gas production will be affected by the source of energy used for desalination. The mix of energy used to supply electricity to the sub-processes affects the overall global warming potential, e.g. a primarily coal powered plant provides electricity with a higher global warming potential than one powered with more natural gas or renewable (e.g. wind) energy. Texas produces all of its own natural gas and about a third of its coal energy predominantly as lignite (Grubert et al., 2012). The potential benefits of using shale gas versus lignite coal fuel for electricity generation warrants a comparison between the carbon emissions and the water consumption from the life cycle of lignite coal and natural gas respectively. The life cycle CO_2 emissions from the lifecycle cradle to grave lignite coal, using a pulverized coal-fired plant are on average 1250 g CO_2 eq/kwh whereas those from natural gas using a natural gas combine cycle power plant are 500 g CO_2 eq/kwh; 2.5 times less than those of coal (Weisser, 2007). However, if we add the carbon emissions associated with desalination in the complete desalination scenario to the carbon emissions from natural gas, which are approximately 1.22 g CO_2 eq/kwh, we still see only a negligible increase in the total CO_2 emissions as compared with that of lignite coal. The life cycle of lignite coal also consumes a lot of water compared with the life cycle of shale gas (Grubert et al., 2012). Lignite consumes 0.61 gal/kwh from cradle to grave in a pulverized coal-fired plant using a once through cooling system, whereas shale gas life cycle from extraction to combustion uses 0.25 gal/kwh of water (Grubert et al., 2012). Lignite coal has a bigger water and carbon footprint than shale gas even under the complete desalination scenario.

This study highlights that there is a tradeoff between GHG emissions and the water scarcity footprint of shale gas production, which varies based on the wastewater treatment option and the source of water used. Advance treatment of produced water does reduce the water scarcity footprint of shale gas production in Texas and may be worth investing in to conserve the water in an arid region with growing water demand. This investment would result in increased GHG emissions associated with the gas produced; however, this could be avoided if the energy used for desalination was sourced from lower-carbon energy sources such as natural gas or wind power.

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Appendix 2.1 – Tables and Figures

Table 2.1. Wastewater Management Scenarios Evaluated

Scenario	Assumptions
Business as usual	Combination of municipal water treatment and reuse, and disposal via deep well injection (U.S. Environmental Protection Agency, 2015)
Complete underground injection	Produced water is disposed of in deep underground injection wells. No water is recycled or reused. The input sources are equal parts of fresh groundwater and surface water.
Partial desalination and partial injection	Half of the produced water is treated using reverse osmosis desalination and reused in future hydraulic fracturing activities, while the rest is disposed of via deep well injection. Of water entering desalination, 20 percent remains as reject concentrated water (Alleman, 2011), which is also deep well injected (Burnett et al., 2004)
Complete desalination and reuse	All the produced water is treated via desalination to pre-use purity levels via reverse osmosis. All but 20 percent of the produced water treated in a desalination plant is reused in drilling and fracking activities; the rest is consumed in the desalination process as reject water (Alleman, 2011) and disposed through deep well injection (Burnett et al., 2004).

Table 2.2. Direct Water Input and Output for each scenario

			Percentage (%)	Water (Ml)	Notes	Source (Reference)
Scenario 1 Business as usual	Input Water	Total	100	35	Business as usual water input quantities and sources	Clark et al., 2011 Clark et al., 2012
		Surface water[2]	47.5	16		EPA, 2015
		Groundwater[2]	47.5	16		EPA, 2015
		Recycled	5	1.7		EPA, 2015
	Output Water	Total Produced water[3]	100	34	Business as usual wastewater management	Clark et al., 2011; Mantell, 2011
		Deep well injection (consumption)[4]	95	33		EPA, 2015
		Reuse/recycle	5	1.7		EPA, 2015
Scenario 2 Complete underground injection	Input Water	Total	100	35	No recycled water used	Clark et al., 2011 Clark et al., 2012
		Surface water	50	18	Equal split between surface & groundwater	EPA, 2015
		Groundwater	50	18		EPA, 2015
	Output Water	Total produced water	100	34	Same as business as usual	
		Deep well injection (consumption)	100	34	Assuming all produced water is deep well injected and consumed	
Scenario 3 Partial desalination and partial injection	Input Water	Total	100	35	Same as business as usual	
		Surface water[5]	31	11	Percentages based on total desalinated water available	
		Groundwater[5]	31	11	Equal split between surface and ground	EPA, 2015
		Recycled and reused after desalination	38	14	All desalinated produced water is reused	
	Output Water	Total produced water	100	34	Same as business as usual	
		Desalination	40	14	Only 80% of desalinated water is available for reuse	Alleman, 2011

[2] The percentages of water sourced from surface water and ground water vary based on studies. According to Nicot et al. 2012, the percentages are surface water (33%) and ground water (60%) whereas EPA (2015) suggests that the percentages are surface water (47.5%) and ground water (47.5%).
[3] Total produced water = produced water + flow back water
[4] Consumption = water that is no longer available to local water users (humans and ecosystems)
[5] This scenario assumes that half of the produced water is desalinated and reused; the input water percentages from ground and surface are calculated over and above the recycled water available from desalination from a previous cycle.

Table 2.2 Continued

			Percentage (%)	Water (Ml)	Notes	Source (Reference)
		Reject water (consumption)	10	3.4	20% of the water is consumed in the desalination process	Alleman, 2011
		Deep well injection (50%) (consumption)	50	17	Assuming that 50% of produced water is deep well injected and consumed	
Scenario 4 Complete desalination & reuse	Input Water	Total	100	35	Same as business as usual	
		Surface water	11	4	Percentages based on total desalinated water available	
		Groundwater	11	4	Equal split between surface and ground	EPA, 2015
		Recycled	78	27	All desalinated produced water is reused	
	Output Water	Total produced water	100	34	Same as business as usual	
		Desalination	80	27	Assuming all produced water is desalinated/reused	Alleman, 2011
		Reject water (consumption)	20	6.9		Alleman, 2011

Table 2.3. Greenhouse gas and water consumption estimation approaches

PROCESS	Inputs/Outputs	ESTIMATION APPROACHES	LCI	DATA SOURCES (References)
Acquisition of water:				
Surface water conveyance and treatment	Water	Energy required for treating surface water in a municipal treatment plant, conveyance of surface water to treatment plant and transportation of fresh water to well site	USLCI	EPRI, 2002; EPA, 2013; Clark et al., 2011
Groundwater extraction	Water	Energy required for pumping groundwater and transportation to well site	USLCI	EPRI, 2002; Clark et al., 2011
Preparation of Well Pad:				
Vegetation clearing		Not estimated		
Well pad construction	Water	Estimated water inputs only	SimaPro raw material	Clark et al., 2011
Well construction & drilling:				
Drilling energy consumption	Diesel	Data collected for Barnett shale	USLCI	Clark et al., 2011
Drilling mud production	Cement	Data collected for Barnett shale	USLCI	Clark et al., 2011; World Steel Association
	Steel		USLCI & World Steel Association	
	Soda ash		Ecoinvent 3	
	Activated Bentonite		Ecoinvent 3	
Drilling water consumption	Water	Data collected for Barnett shale	SimaPro raw material	Werline, 2011
	Diesel for transportation	Estimated for Barnett shale	USLCI	Clark et al., 2011
Drilling wastewater	Water	Long term groundwater	SimaPro emission category	
Hydraulic fracturing:				
Pumping energy	Diesel	Estimates for Barnett shale	USLCI	Clark et al., 2011

Table 2.3 Continued

PROCESS	Inputs/Outputs	ESTIMATION APPROACHES	LCI	DATA SOURCES (References)
Additives	Hydraulic Fracturing Fluid Components	A variety of 3 - 12 chemical additives in various percentage compositions	Ecoinvent 3	U.S. Department of Energy, 2009; Chesapeake Energy, 2012
Acid	Hydrochloric Acid	Estimates of quantities are taken from ranges provided in literature (Stringfellow et al., 2014; McCurdy, 2011) for unconventional shale gas production or values published specifically for Barnett shale (Clark et al., 2011)	Ecoinvent 3	Clark et al., 2011
Proppant	Sand		Ecoinvent 3	Clark et al., 2011
Crosslinker	Ethylene glycol		Ecoinvent 3	Stringfellow et al., 2014
Breaker	Magnesium oxide		Ecoinvent 3	Stringfellow et al., 2014
Clay Stablilizer	Sodium chloride		Ecoinvent 3	Stringfellow et al., 2014
PH adjuster	Sodium hydroxide		Ecoinvent 3	Stringfellow et al., 2014
Corrosion Inhibitors	Acetaldehyde Acetone Formic acid Isopropanol Methanol		Ecoinvent 3	Stringfellow et al., 2014; McCurdy, 2011
Iron Control	Citric acid		Ecoinvent 3	Stringfellow et al., 2014
Surfactant	Methanol		Ecoinvent 3	Stringfellow et al., 2014
Gelling component	Ethylene glycol		Ecoinvent 3	Stringfellow et al., 2014
Biocide	Ammonium chloride		Ecoinvent 3	Stringfellow et al., 2014
Scale Inhibitor	Polyacrylamide		Ecoinvent 3	Clark et al., 2011
Water consumption	Water	Estimates for Barnett shale	SimaPro raw material	Clark et al., 2011
Methane emissions	Fugitive Methane	Emissions during flowback and drilling stages Venting (85%) and Flaring (15%) CH_4 to CO_2 conversion factor	SimaPro emission category	Wood et al. 2011; Howarth et al., 2011; Skone et al., 2011; Hultman et al., 2011
Flowback water	Water	Long term groundwater	SimaPro emission category	Mantell et al., 2011

Table 2.3 Continued

PROCESS	Inputs/Outputs	ESTIMATION APPROACHES	LCI	DATA SOURCES (References)
Well completion:				
Produced shale gas	Natural gas	Converted cubic meters to MJ/well	USLCI	Howarth et al. 2011
Total produced water	Water	Produced water over a lifetime of well	SimaPro raw material	Clark et al 2011; Clark et al 2012
Wastewater disposal:				
Deep well injection	Wastewater	Quantity disposed, fuel used, distance traveled	SimaPro emission category	EPA, 2015; Clark et al., 2011
Municipal Water Treatment	Wastewater	Quantity transported and treated	ELCD	EPRI, 2002; EPA, 2013; Clark et al., 2011
Desalination (Reverse Osmosis)	Wastewater	Assumed current resources have the ability to treat produced water from Barnett shale play	ELCD	Thiel et al. 2015; Clark et al., 2011; Nicot et al., 2006

Table 2.4. Energy and diesel inputs under each scenario

Scenarios		Amount	Units	Source (Reference)
Scenario 1	Produced water	3.43×10^7	L/well	Clark et al., 2011; Mantell et al., 2011
Deep Well Injection	Volume deep well injected	3.26×10^7	L/well	EPA, 2015
	Truck fuel consumption (loaded)	5	mpg	Clark et al., 2011
	Truck fuel consumption (unloaded)	7	mpg	Clark et al., 2011
	Volume of water per truck	2.08×10^4	L/truck	Clark et al., 2011
	Distance to transport fluid to disposal well	10	miles	Clark et al., 2011
	Diesel for well injection	2.03×10^4	L/well	Calculated
Recycle/reuse (municipal water treatment)	Volume recycled/reused	1.71×10^6	L/well	EPA, 2015
	Energy for Water treatment	0.0053	kwh/L	EPRI, 2002
	Total energy requirement	636	kwh	Calculated
	Distance to transport recycled fluid to and from site	4	miles	Clark et al., 2011
	Diesel for recycling	212	L	Calculated
	Total diesel used in Scenario 1	2.05×10^4	L	Calculated
Scenario 2	Produced water	3.43×10^7	L/well	Clark et al., 2011; Mantell et al., 2011
Complete underground injection	Volume deep well injected	3.43×10^7	L/well	Assumption
	Number of trucks	1,647	**#**	Calculated
	Distance to transport fluid to disposal well	10	Miles	Clark et al., 2011
	Total diesel used in Scenario 2	2.14×10^4	L	Calculated
Scenario 3	Produced water	3.43×10^7	L/well	Clark et al., 2011; Mantell et al., 2011

Table 2.4 Continued

Scenarios		Amount	Units	Source (Reference)
Partial desalination &	Volume desalinated (50%)	$1.71x10^7$	L	Assumption
	Volume desalination output (40%)	$1.37x10^7$	L	Alleman, 2011
	Distance to transport fluid to plant and back	100	Miles	Nicot et al., 2006
	Diesel to transport water to plant	$5.35x10^4$	L	Calculated
	Diesel to transport water to site	$4.28x10^4$	L	Calculated
	Energy for desalination	0.23	kwh/L	Thiel et al. 2015
	Total energy requirement	$2.76x10^5$	kwh	Calculated
	Volume of reject water (10%)	$3.43x10^6$	L	Alleman, 2011
	Diesel to disposal well (reject water)	$2.14x10^3$	L	Calculated
Partial injection	Volume deep well injected (50%)	$1.72x10^7$	L	Assumption
	Diesel to disposal well	2,825	L	Calculated
	Total diesel used in Scenario 3	$1.09x10^5$	L	Calculated
Scenario 4	Produced water	$3.43x10^7$	L/well	Clark et al., 2011; Mantell et al., 2011
Complete desalination and reuse	Volume desalinated (100%)	$3.43x10^7$	L/well	Assumption
	Volume desalination output (80%)	$2.74x10^7$	L	Alleman, 2011
	Volume of reject water (20%)	$6.86x10^6$	L	Alleman, 2011
	Diesel to desalination plant	$1.07x10^5$	L	Calculated
	Diesel to fracturing site	$8.55x10^4$	L	Calculated
	Diesel to disposal well (reject water)	$4.27x10^3$	L	Calculated
	Total energy requirement	$5.52x10^5$	kwh	Calculated
	Total diesel used in Scenario 4	$1.97x10^5$	L	Calculated

Table 2.5. Water Consumption & Water Scarcity Footprint

		Water Consumption *Direct* (L)	**Water Consumption *Indirect* (L)**	**Water Scarcity Footprint *Direct* (L world equivalents)**	**Water Scarcity Footprint *Indirect* (L world equivalents)**	**Water Scarcity Footprint *Combined* (L world equivalents)**
Scenario 1	**Business as usual**	3.26E+07	1.53E+07	1.14E+08	1.45E+08	2.60E+08
Scenario 2	**Complete injection**	3.43E+07	1.53E+07	1.20E+08	1.45E+08	2.66E+08
Scenario 3	**Partial desalination and partial injection**	2.06E+07	1.61E+07	7.23E+07	1.53E+08	2.26E+08
Scenario 4	**Complete desalination and reuse**	6.86E+06	1.72E+07	2.41E+07	1.64E+08	1.88E+08

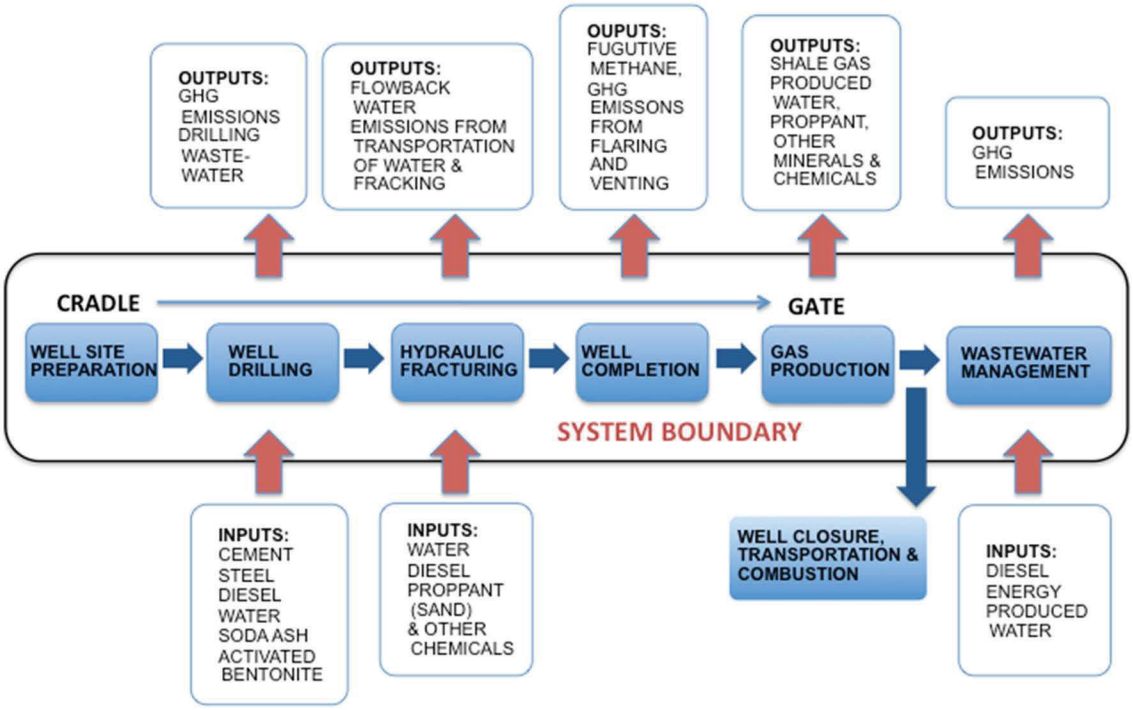

Figure 8. System Boundary Schematic

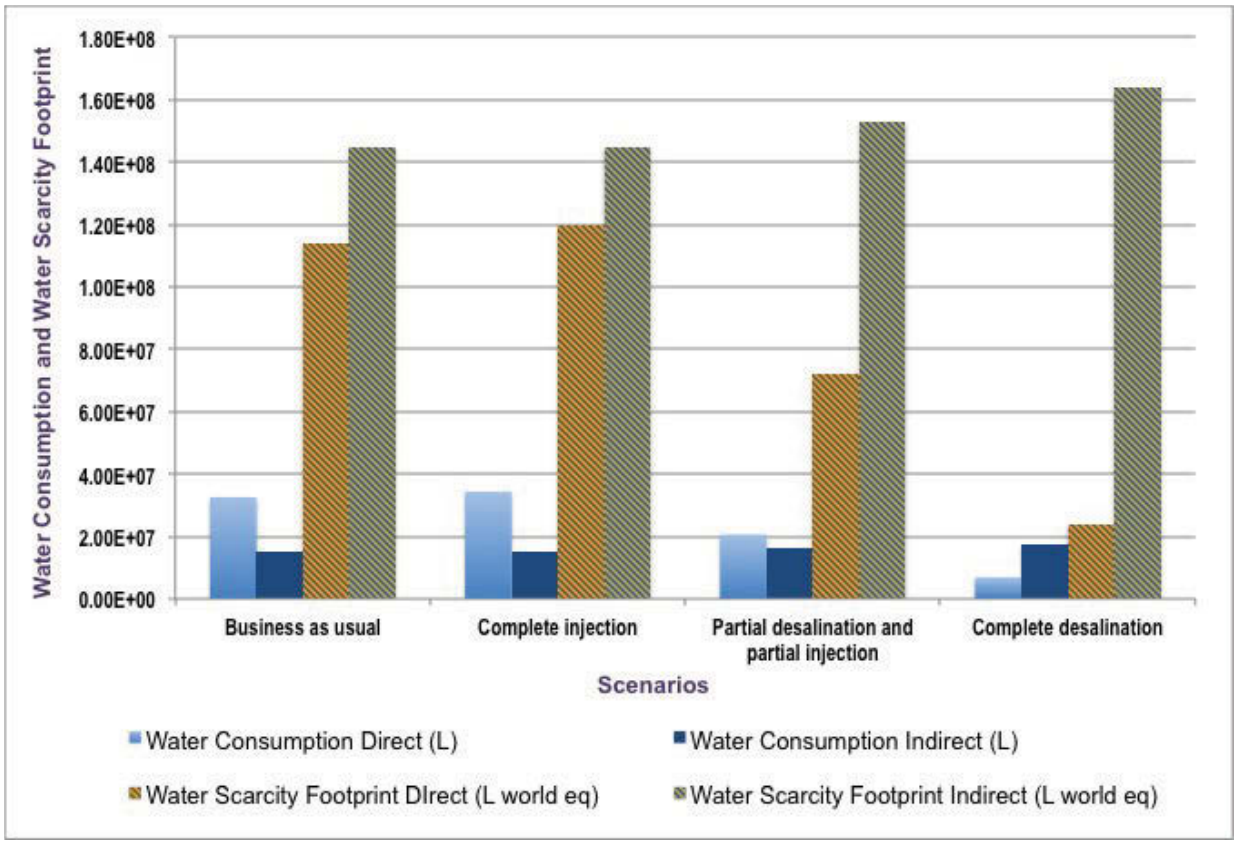

Figure 9. Inventory Water Consumption and Water Scarcity Footprint for each scenario

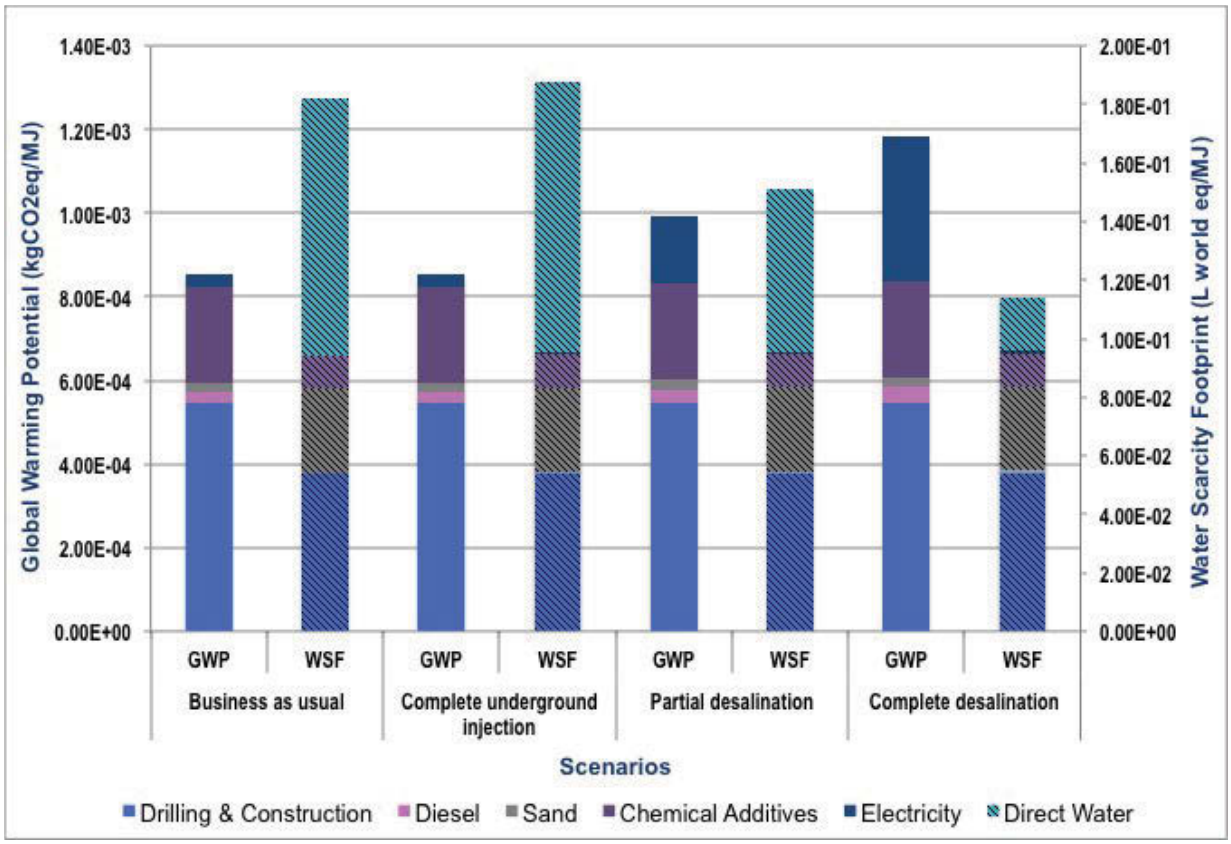

Figure 10. Global Warming Potential and Water Scarcity Footprint for each wastewater management scenario and input category

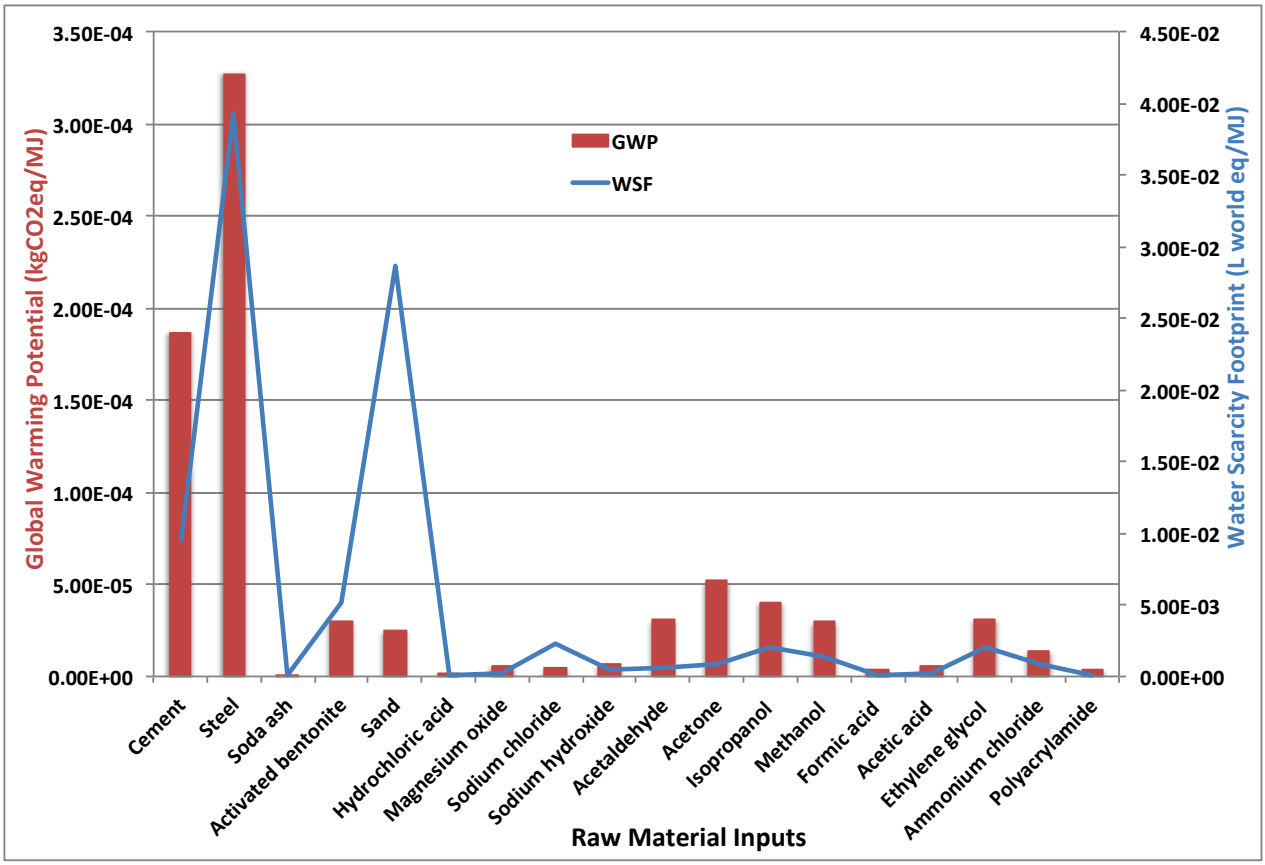

Figure 11. Global Warming Potential and Water Scarcity Footprint for all non-energy raw material inputs for business as usual scenario

Chapter Three – Climate Adaptation Scenarios For The Hydraulic Fracturing Industry In Texas

This chapter is yet to be submitted for publication by Syeda Mariya Absar, Benjamin L. Preston, Anne-Marie Boulay, Adam Taylor, Ryan McManamay:

Absar, S. M., Preston, B. L., Boulay, A.-M., Taylor, A., McManamay, R. (2017). Climate change adaptation of energy-water nexus and tradeoffs for hydraulic fracturing in Texas.

The article is presented in its original form, formatted for this dissertation including renumbering tables and figures. Author was lead author and lead investigator on study. Co-author Benjamin L. Preston supervised the development of this work and provided critical revisions for important intellectual content. Co-author Anne-Marie Boulay helped augment the analysis with her expertise in water scarcity footprint calculation, and co-author Adam Taylor helped in data interpretation and manuscript evaluation.

Abstract

Energy and water are interdependent sectors of the economy and due to their interdependent nature, they need to be jointly managed to mitigate risks associated with climate change and competition from other sectors. To understand this interdependency and to help with decision-making with regard to adaptation, we look at hydraulic fracturing in Texas as an illustrative example of an industry that uses energy and water intensive processes in a drought prone region. The objective of this study was to develop a coupled life cycle assessment modeling framework to quantify the inherent tradeoffs around greenhouse gas emissions and water consumption within an energy system. Multiple socioeconomic scenarios, developed around alternative policy and technology choices were used to parameterize this model in order to determine the best policy levers to adapt this energy system to future stresses.

Introduction

Energy and water are indispensable inputs to any economy. Growing awareness of the implications of the interdependencies that exist between the two sectors for sustainability is leading to them being increasingly framed as a joint energy-water nexus (EWN). Water is used directly for electricity production through hydroelectric power generation and indirectly as a coolant for thermoelectric power plants. Meanwhile, the energy sector is critical to the management of water. Significant electricity is used to withdraw, treat, and transport water and to treat wastewater. This nature of the coupling between energy and water resources varies significantly with geography and technology as well as over time. A constraint in one sector can lead to a constraint in the other (Ernst and Preston, 2017). Failure to consider the interdependent dynamics of the EWN introduces vulnerabilities. For instance, climate change introduces uncertainties

in water resource availability and predictability. These may lead to constraints in the energy sector. Similarly, grid outages or other failures in the energy system can become constraints to the water and wastewater treatment sectors (Stillwell et al, 2011; Scanlon et al., 2013; DOE, 2014).

The carbon emissions from the production, consumption, and waste within the EWN contribute to climate change. Climate change in return poses increasing stress on the EWN through increased frequency, intensity, and/or duration of droughts, heat waves, and extreme rainfall events (Roy et al., 2012; Scanlon et al., 2013). Population growth and increasing temperatures drive up the demand for both energy and water resources, which can pose significant additional stress to the energy and water supply systems, especially in water-stressed regions of the U.S. where there are other competing uses of water such as agriculture, industry, and households (Vörösmarty et al., 2000).

Traditionally, climate adaptation is oriented toward individual sectors. This overlooks the complex interdependencies between sectors; adaptation actions that are isolated to one sector can lead to increased vulnerabilities in another. For example, some adaptation strategies can give rise to increased resource use and environmental degradation (Scott et al., 2011). Hence, the most effective and efficient approach for adapting the energy and water sectors to the effects of climate change is to do so in the context of the EWN (Ernst & Preston, 2017; Scott et al., 2011; DOE, 2014). Such integrated framings of adaptation can assist in identifying tradeoffs between the energy and water sectors such as increasing energy demand constraining efforts to conserve water for other competing uses (Ernst and Preston, 2017; Scott et al., 2011). Climate change makes such tradeoffs unavoidable, but they need to be made explicit if decision-makers are to manage them in a manner that maximizes societal benefit.

This study focuses on the tradeoffs between greenhouse gas mitigation and water conservation in the energy-water-nexus and how adaptation policy can influence these tradeoffs. An illustrative example of such a tradeoff is the hydraulic fracturing process in water stressed regions such as Texas (Scott et al., 2011; Tidwell et al., 2013; Small et al., 2014). Hydraulic fracturing, or fracking, is the process of injecting pressurized water and chemicals in a subterraneous rock formation (i.e. shale) to create fractures that release natural gas or oil to the surface (EPA, 2015). Fracking has given rise to increased energy independence, economic development, and reduction of greenhouse gas emissions in the United States. However, it is a highly water intensive process requiring 2–9 million gallons of water per well (Scott et al., 2011) which becomes a particular concern in regions with uncertain water supply and abundance of natural gas reserves such as Texas (Nicot & Scanlon, 2012; Roy et al., 2012; Tidwell et al., 2013). Due to limited published literature around climate change and impacts on the energy-water nexus in fracking (Scott et al., 2011; Small et al., 2014; Tan &

Zhi, 2016), this study takes a detailed look at the complexity of this nexus with a particular focus on the Barnett shale play in Texas, and its adaptation to climate change.

One way to understand the implications of shale gas production for the EWN is to use a systems approach. A well-established and widely used systems approach is Life Cycle Assessment (LCA) (Curran, 1996; Rebitzer et al., 2004; Pennington et al., 2004). Traditionally, LCA is used to understand the sub-components of any product or process to quantify all the raw materials, energy inputs, and their environmental impacts at each stage of production (Curran, 1996). LCA is widely used for quantifying the energy and water footprints within shale gas production (Jiang et al., 2011; Grubert et al., 2012; Jiang et al., 2014; Nicot & Scanlon, 2012) as well as its inherent tradeoffs (Perrone et al. 2011; Bazilian et al., 2011). Nevertheless, the capacity of LCA is limited with respect to examining uncertain energy and water futures in terms of technology, governance, and other socioeconomic factors. To address these limitations, Björklund (2002) and Huijbregts (1998) assert that scenario analysis can be combined with LCA to better understand the implications of uncertainty on decision-making. The use of disparate scenarios can enhance the prognostic value of LCA and allows for a *Prospective LCA* (Pesonen et al., 2000; Spielmann et al., 2005) to explore various energy and technology pathways.

One approach to evaluating the tradeoffs associated with greenhouse gas emissions and water use from hydraulic fracturing processes is to model the outcomes associated with various technology pathways (Scott et al., 2011; Kriegler et al. 2012; Ghanadan & Koomey, 2005; Bazilian et al., 2011). To this end, LCA was used in combination with energy and water technology scenarios based on the shared socioeconomic pathways (SSPs) (O'Neill et al. 2014b) in order to better understand the consequences of waste water treatment technology choices for water use and greenhouse gas emissions from fracking. The intent of this paper is to identify the most effective wastewater management technology options to achieve a desired balance between greenhouse gas emissions and water conservation. The results of this study demonstrate the energy-water tradeoffs associated with different technology options, which can subsequently inform the design of policy and technology options that achieve the preferred balance with respect to environmental objectives.

Methods

Description of study region

Surface water supply in Texas is heavily reliant on reservoir water storage and about 40 percent of water used by municipalities comes from groundwater (George et al., 2011). In 2010, Texas had the third highest groundwater

withdrawals in the country and the second highest withdrawals for mining purposes (Maupin et al., 2014). More than half of the water used for fracturing the Barnett shale is acquired from groundwater (EPA, 2015). In 2015, Texas was the largest shale gas producing state in the US (Tran, 2014) with the Barnett Shale producing 30 percent of the total U.S. shale gas (EIA, 2017) from a technically estimated shale gas reserve of 4.7 trillion cubic feet (EIA, 2015). Since 2008, more than 17,000 oil and gas wells have been drilled in the Barnett Shale (Nicot et al., 2014) and another 14,000 are predicted by 2030 (Browning et al., 2013). Fracking is water intensive, requiring up to 15 million liters of water in the lifetime of a well (Mantell, 2011; Clark et al., 2011; Scott et al., 2011). According to water budget predictions in the area, by 2025, the aquifers may no longer be able to sustain the anticipated water demand (TWDB, 2007). As the metropolitan area of Dallas-Fort Worth expands, the growing population's water demand and the water demand of the gas industry will compete in what is already a water scarce area.

Barnett shale generates more than 3,785 liters (>1000 gallons) of water per million cubic feet (~1 MJ) of shale gas produced due to the presence of natural formation water in and around the shale. This volume is sufficient to provide approximately 10 to 15 percent of the total water needed to fracture a new well. Large volumes of produced water create a feasible source of water for additional fracking operations (Mantell, 2011). However, 95 percent of produced water in Barnett is deep well injected into an extensive naturally occurring network of salt water Class II disposal wells that are permitted by the Environmental Protection Agency (EPA) for injection of fluids associated with oil and gas production (EPA, 2008, 2015). These wells provide an economical and low energy intensive alternative to advanced reuse options, such as reverse osmosis or desalination (Mantell, 2011), albeit at the cost of large volumes of water permanently lost from the watershed (TWDB, 2007). In contrast, one of the technologies recommended by EPA for the treatment of produced water include desalination by reverse osmosis (Alleman, 2011). These can prevent water from being lost from the watershed, but is an energy intensive process (Mantell, 2011; Hayes, 2011). Although the Barnett area is not yet equipped with desalination plants that have the capacity or technology to pretreat produced water, some pilot reverse osmosis desalination plants are currently being tested (Hayes, 2011; Alleman, 2011). Hence, the changing nature of water treatment technologies in Barnett has the impetus to force potential trade-offs between energy intensive or water intensive approaches, which have different implications for climate change vulnerability.

When it comes to managing water supplies, multiple authorities exercise overlapping jurisdiction in Texas. In the absence of a cohesive federal regulatory policy around fracking, the onus of regulation falls upon individual states. Many of the states involved with the gas boom have taken legislative or administrative

actions to regulate some aspects of hydraulic fracturing in order to protect water quality. For instance, Colorado and Wyoming require disclosure of chemicals used in fracking; However, in Texas, fragmented regulatory bureaucracy, pro oil and gas legal and administrative structure, and lack of a strong environmental protection culture (Rahm, 2011), have led to little environmental regulation of fracking. These characteristics pose potential challenges to the effective adaptation of the expanding fracking industry to a changing climate and its implications for water resource availability (Browning et al., 2013). However, such challenges will be strongly influenced by the future evolution of the water and energy sectors as well as how alternative potential policy levers are applied in the future by different actors.

Approach to Prospective LCA

An LCA using various instances of a process, whether currently used or perceived for the future, to carry out an improvement analysis of the system, with regard to one or all of the impact categories, is known as Prospective or a future-oriented LCA (Pesonen et al., 2000; Spielmann et al., 2005). The approach to prospective LCA is comprised of three components: (1) the development of alternative state level storylines or scenarios using the global shared socioeconomic pathways; (2) the articulation of policy assumptions and technology choices consistent with alternative state-level scenarios; and (3) the use of policy and technology assumptions, consistent with alternative scenarios, within multiple LCA experiments or prospective LCA. Each of these components are explained in detail in the subsequent sections. An estimation of the impact categories of greenhouse gas (GHG) emissions and water scarcity footprint, using prospective LCA, helps understand the environmental impacts of energy and water use in a system. This approach and its sub-components are also highlighted in the conceptual model shown in Figure 12.

Scenarios Framework

Scenarios are one of the most common approaches to representing future socioeconomic conditions and trends (Preston et al., 2011; Ebi et al., 2014; Mekonnen et al., 2016), and are critical tools for exploring future consequences and management responses associated with climate change (Nakic´enovic´ and Swart, 2000; van Ruijven et al., 2014). Socioeconomic pathways of disparate development futures can be used to explore alternatives to a given reference path and their associated tradeoffs. This can help decision-makers avoid path dependence and evaluate alternative response options before making long-term, binding decisions. The Shared Socioeconomic Pathways (SSPs) are the latest generation of socioeconomic storylines for climate change research and assessment. They are components of the parallel scenario process (Moss et al., 2010), which is also comprised of representative concentration pathways to force Earth system models as well as shared policy assumptions to characterize

climate-related risks and response options for future climate change and its impacts. The global SSPs provide information on global driving forces and socioeconomic elements necessary for any development pathway, but generally lack detail at the regional, national, or local level (Kriegler et al., 2012; Moss et al., 2010; O'Neill et al., 2012, 2014 a, b). Nevertheless, various studies have demonstrated that the SSPs can be extended to carry out more geographically-refined climate change mitigation or adaptation studies (Ebi et al., 2014; Kriegler et al., 2012; Moss et al., 2010; O'Neill et al., 2014a; Absar and Preston, 2015). Absar & Preston (2015) recently developed such extensions for the U.S., with a particular emphasis on developing storylines for the energy and water sectors in the U.S. Southeast and Gulf Coast.

The current study further extended these storylines to the state of Texas in order to develop the technology and policy context for the state's future fracking industry. These extensions were developed by applying the Factor–Actor–Sector (F-A-S) framework (Kok et al., 2006), following the approach of Absar & Preston (2015). Within this framework, a sector represents a sub-component of a national or social system. An actor represents an individual or organization of individuals with the capacity to influence change. A factor represents an aspect of a social or natural system around which there are broad policy issues of particular interest (Kok et al., 2006). The Factor–Actor– Sector framework was selected for developing the extensions for Texas to maintain consistency among the global, national, and sub-national storylines that have been developed previously (see Figure 13 for illustration of the nesting framework). For factors and actors, the storyline elements for Texas remained the same as those for the sub-national storylines (Absar & Preston, 2015), however, the focus narrows further to only two sectors; water and energy (Appendix A). As in the case of the sub-national storylines, the state level storyline elements were developed using sub-national storylines and scenarios that contained state level details and projections for Texas particularly around the evolution of the energy and water sectors (EIA, 2017; TWDB, 2017 State Water Plan; Scanlon et al., 2013). Although the state level storyline elements were largely based on qualitative information, some quantitative indicators were developed to better understand the relative trends and dynamics of key factors within the state. These quantitative indicators were developed for state population and GDP by spatially disaggregating the U.S. population (IIASA-WIC v9) and GDP (IIASA-GDP v9) projections within the International Institute for Applied Systems Analysis (IIASA) SSP database version 0.93 (IIASA, 2012) to the state level using the Integrated Climate and Land Use Scenarios (ICLUS) sponsored by the U.S. Environmental Protection Agency (Bierwagen et al., 2010) and Bureau of Economic Analysis data (BEA, 2013), respectively. The method to develop the state level population and GDP projections under each SSP was adopted from Absar & Preston (2015). These trends are shown in Figure 14.

Shared Policy Assumptions

The SSPs do not include explicit assumptions about future emissions, or climate change impacts and therefore need to be supplemented with key policy attributes relating to mitigation and adaptation in order to integrate local scale climate impacts and adaptation into the scenario analysis (Riahi et al., 2017; Cradock-Henry et al. 2017, submitted). As proposed, the SPAs include only explicit mitigation or climate policies to provide a third dimension to the scenario matrix architecture (Kriegler et al., 2012, 2014; van Vuuren et al., 2014). However, as argued by Frame et al. (2016) and Cradock-Henry et al. (2017, submitted), SPAs should contain both climate and non-climate policy assumptions in order to maximize their utility for the broadest range of stakeholders and decision contexts. Policies that focus on greenhouse gas mitigation, for example, can be used to identify mechanisms by which society can overcome challenges to mitigation associated with different SSPs. However, to explore the mechanisms by which society can overcome challenges to adaptation requires a different set of policy assumptions including non-climate policies (Cradock-Henry et al. 2017, submitted). Hence, the SPAs for this study focus on both mitigation and adaptation policy assumptions relevant to the fracking industry in Texas (Appendix B). This enables the analysis of not only how different socioeconomic futures could affect technology choices within the fracking industry, but also the underlying policy environment consistent with those choices.

The rapidly evolving landscape of shale gas governance in the U.S. has challenges and opportunities associated with the current decentralized system of regulation in Texas. In order to develop the SPAs, the emerging approaches to shale gas governance in all shale gas producing states were reviewed (Olmstead & Richardson, 2014; Rahm, 2011; Rahm et al., 2013; Jenner & Lamadrid, 2013; Small et al., 2014). New governance initiatives were considered to address the complexities of the shale gas system and to reduce the many key uncertainties needed to adapt wastewater management in fracking operations in Texas. Some policy instruments included: (1) command-and control or prescriptive approaches including technology standards and performance standards, (2) market based policy instruments such as taxing negative externalities, subsidizing positive practices, and having market tradable pollution permits, (3) the regulation and monitoring of chemicals used in fracking and limiting deep well injection to prevent water stress and other associated environmental externalities.

SPAs articulate fracking relevant policies and technology choices, which are converted into quantitative parameters to be used in LCA to compare energy and water tradeoffs under each SSP (Figure 4). How the SSP narratives are translated into SPAs, technology choices, and LCA parameters is shown in the matrix in Table 3 and explained in the results section. However, it should be noted that, much like socioeconomic futures themselves, the SPAs represent societal choices that are inherently uncertain and therefore cannot be predicted. Rather, they represent policy environments deemed consistent with each SSP

and capture a broad range of alternative policy orientations relevant to the future of hydraulic fracturing.

Prospective lifecycle assessment using socioeconomic pathways

This study uses the LCA modeling framework developed by Absar et al. (2017, Submitted). The shale gas production process was developed in the SimaPro LCA software package (PRé-sustainability, 2014), using the life cycle inventory of inputs and emissions of relevant "upstream[6]" process data contained in the U.S. Life Cycle Inventory Database (National Renewable Energy Laboratory, 2012) and the Ecoinvent v3 (Weidema et al., 2013) database. The sub-process data for energy and material flows in a shale gas production process were also taken from Absar et al. (2017, Submitted). The data and sources for the process input and output water for each SSP are shown in Table 3.1. The energy and diesel input data for each SSP is shown in Table 3.2. The goal of this LCA model is to understand the GHG emissions and water consumption associated with shale gas production in the Barnett, under the SSP extensions and their associated SPAs (Appendix B). The reference flow for this study is one mega joule of gas produced from typical shale wells. The impact categories used to quantify the GHG emissions and water consumption are *global warming potential* (GWP) expressed as kilograms of carbon dioxide equivalent per mega joule of natural gas produced (kgCO2eq/MJ), and the *water scarcity footprint* (WSF) reported in liters world equivalent per mega joule of gas (L world eq/MJ) respectively. The analysis is 'cradle-to-gate:' the boundary of the shale gas production process includes well pad preparation, drilling, hydraulic fracturing, well completion, gas production and wastewater management (Figure 8). The SPAs representing alternative scenarios are quantified as model parameters, with regard to energy and material inputs, and environmental flows to model the different instances of the same process in a prospective LCA (Pasqualino et al., 2009; Lundie et al., 2004; Boer et al., 2007).

To calculate the life cycle impact categories of global warming potential and water scarcity footprint, the methods explained in Absar et al. (2017, submitted) were used. For GWP, the *Tool for the Reduction and Assessment of Chemical and other environmental Impacts* (TRACI v2.1) model (Bare, 2011) was used. This calculation was based on characterization factors that quantify the relative impacts of various gases (e.g. CO_2 and methane) in terms of CO_2 equivalents per unit of shale gas energy produced (kg CO_2 eq/MJ). The sources of GHG emissions considered in this LCA include: emissions from the production and transportation of materials involved in the well development activities (such as trucking water); emissions from fuel consumption for powering the drilling and fracturing equipment; methane leaks and fuel combustion emissions associated with gas production. To calculate the water scarcity footprint, a consensus-based

[6] Upstream processes provide the materials and energy inputs to the process under consideration. These generally occur off-site but their environmental impacts are attributed to the process.

method called Available WATer REmaining (AWARE) is used (Boulay et al., 2017). AWARE is calculated on a per area basis in a watershed, after the demands of humans and aquatic ecosystems have been met, calculated in liters world equivalents per mega joules of shale gas produced. Water consumption was assessed from well pad preparation, well drilling and construction, hydraulic fracturing, shale gas production, and all the associated upstream processes (Absar et al., 2017, submitted). The resulting GWP and WSF for each SSP are shown in Figure 15.

Results

In the shale gas extraction process, the intensity of water use and the energy dissipated depends on the technology adopted for the wastewater management of produced water from fracking. The amount of energy used in desalination is much higher than energy needed in transporting and injecting water into an aquifer. Using a coupled methods approach, using multiple scenarios, allows us to dig deep into the water and energy use within various instances of a select energy system and to understand the hot spots and opportunities that exist in making the system more sustainable and resilient.

Policy and technology assumptions for SPAs

The policy assumptions present some favorable local conditions for the assumed technologies and adaptation objectives to be met under each SSP. These policy instruments are designed to bring about a desired effect especially in the regulation of the fracking industry with respect to climate change. For example, for SSP1, a sustainable pathway with lower environmental externalities and efficient resource use, policy instruments that enable reliance on renewable energy and water conservation were selected as SPAs. These include deregulation of energy markets, other legislative mandates and financial incentives enabling the integration of wind in the energy grid such as the renewable portfolio standard and state level tax incentives. A severance tax on the quantity of water consumed in fracking, and incentivizing use of desalination technologies through tax credits help water conservation and reuse in the industry. Similarly for SSP3, a fragmented world, with high challenges to both mitigation and adaptation due to slow technological change and deregulated water management, has policies that allow for both desalination and deep well injection of wastewater based on the resources available to the producers. These policies include state legislation limiting water use via heavy impact fee and cap and trade of water rights to disposal wells. State level subsidies for water infrastructure allow some investment in wastewater treatment while a decentralized regulatory system with multiple authorities overseeing water management prevents access to sophisticated infrastructure by all producers. The detailed policy and technology assumptions, matching the narratives of SSPs 1,2,3 and 5, are provided in Appendix B. The policy instruments allow mitigation and adaptation objectives of the SSP narratives to be met using the

technologies selected for each SSP and quantified for the prognostic LCA model to compare associated energy and water tradeoffs (Figure 15).

Policy assumptions influence technology choices or pathways unique to a given SSP. In this study, the technology pathways determine the technologies involved in wastewater management of the fracking industry. These technology choices are based on the current state of technology used to treat produced water. For example, one technology choice around wastewater management for SSP1, with low challenges to mitigation and adaptation, is *carbon neutral desalination* wherein a high percentage of input water is taken from recycled sources, and all of the produced water is desalinated for reuse to reduce the water scarcity footprint. There is increased reliance on renewable energy resources to keep greenhouse gas emissions low. These technology choices are quantified and reflected in the data parameters of the LCA model (Table 3.3). Similarly, the technology choice for SSP2 is *complete underground injection*, which is closest to the business as usual wastewater management practices. For SSP3, *partial desalination and partial injection* is selected to reflect decentralized wastewater management, and for SSP5, *complete desalination* is selected to reflected high fossil energy demand and highly engineered infrastructure (see Table 3.3 for details).

Prospective LCA

Figure 15 shows global warming potentials and water scarcity footprints associated with each SSP scenario, based on the quantified SPAs (Table 3.3). The model parameters around water and energy use reflect the SSP narratives. For SSP 1, a sustainable future characterizes low challenges to adaptation and mitigation, which is reflected in the resulting low carbon and water footprints. For SSP 2, with intermediate challenges, the WSF is higher than in a sustainable future due to deep well injection, which reflects high water consumption from the system but low energy use is evident in the low GWP as most energy use is in the form of diesel used in transporting the water to the injection wells. For SSP3, the WSF is lowered by the use of desalination albeit at the cost of higher GWP as compared to SSP2 and in SSP 5, lower WSF is accomplished by using more fossil energy in desalination.

Discussion

Hydraulic fracturing has been a game changer in recent years, which has enabled natural gas, in particular, to play an integral role in US energy policy, technology, and security. With climate change and other stressors, it is difficult to predict energy and technology futures. The SSPs provide a flexible tool to explore the uncertainty associated with the evolution of technology pathways and their implications for the pursuit of climate-resilient fracking operations. This framework also allows technology choices to be quantified for testing in a modeling environment to understand tradeoffs related to resource use.

The results of the prognostic LCA conducted in this study show a clear tradeoff between the mitigation and adaptation of the fracking industry except for SSP1, where policy and technological choices around desalination and renewable energy use enable lowering of both the greenhouse gas emissions and water consumption to allow for a sustainable future consistent with the SSP1 narrative around low challenges for adaptation and mitigation. For SSP 5, the technology choices for wastewater management albeit identical to SSP1, reduce vulnerability to water stress but the tradeoffs of energy use exacerbate mitigation. This is due to the differences in the energy mix, which is reflected in the GWP of the two scenarios. The SSP5 world, with high challenges for mitigation and low challenges for adaptation, propagates investing in infrastructure for the adaptation of the water sector such as desalination but is fossil fuel driven which is why the greenhouse gas emissions remain high as reflected in Figure 15.

The current study demonstrates that there are significant trade-offs associated with fracking technologies and processes that affect sustainability. The prognostic modeling framework uses GHG emissions as a determinant of climate change outcomes and water consumption as a determinant of potential water scarcity. Results from LCA for different SSPs indicate that a system that has higher carbon footprint has a lower water footprint and vice versa (see also Mekonnen et al., 2016). Such trade-offs pose challenges for setting priorities for overall environmental improvement. If fracking is a component of Texas' energy future, it may not be possible to minimize both water consumption and energy consumption. Thus industry and regulatory decision-makers must make choices regarding how to balance outcomes across these resource sectors while also managing potential risks associated with climate change. While the subjective nature of these decisions limits the ability of analysis and modeling tools to identify clear solutions, LCA helps quantify the implications of alternative technology pathways that can help guide the appropriate reconciliation of trade-offs.

Given the trade-offs inherent in the management of wastewater from fracking, a particular opportunity created by the integration of scenarios with LCA is the identification of decision points that can transition fracking from one technology pathway to another. This enables decision-makers to avoid path-dependence that can lock the industry into long-term decisions that can undermine efforts to adapt to the changing climate (Ernst & Preston, 2016; Preston, 2013). For example, in the event that water resources in Texas come under significant pressure due to the effects of climate change and competition among water users, investment decisions regarding fracking technology that prioritize energy conservation may reduce industry resilience. This process of transitioning from one path to another is facilitated by the SPAs which articulate the policy choices that enable each pathway to manifest. In principle, the prior analysis of

alternative scenarios and policy assumptions with LCA could enable decision-makers to anticipate the consequences of specific policies before they are implemented. Alternatively, should policy-makers choose to transition to a new path, the SPAs outline the policy portfolios that should be considered to facilitate that transition. The SSPs and SPAs therefore expand traditional LCA in decision-relevant directions by creating a policy context that can be used for interpreting LCA results.

Conclusion

This study developed and tested a coupled modeling framework that allows for adapting the EWN to the effects of climate change. This model quantifies the energy-water tradeoffs associated with different technology options in an energy system, to help inform policy with respect to environmental objectives. This framework was composed of three components; the alternative state level storylines or scenarios which were developed using the global shared socioeconomic pathways; policy assumptions and technology choices consistent with the alternative state-level scenarios; and the use of these policy and technology assumptions within multiple LCA experiments or prospective LCA to understand the associated tradeoffs. Results from LCA for different SSPs indicate that in most cases a system that has higher carbon footprint has a lower water footprint and vice versa. If an energy future beckons to minimize both water consumption and energy consumption then the industry and regulatory decision-makers must make policy and technology choices for sustainable resource management and minimizing potential risks associated with climate change. In this regard, prospective LCA helps quantify the implications of alternative technology pathways by highlighting the inherent tradeoffs and providing decision points and policy portfolios that can transition an industry from one technology pathway to another. This study can be used in scaling up the environmental impacts of hydraulic fracturing industry in Texas with the use of geospatial data and bottom up scenarios around trends in fracking, population growth, water availability and other competing water users in the region to understand the evolution of this nexus and how specific policies can affect this entire region.

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Appendix 3.1 – State level SSP Storylines for energy-water nexus in Texas

State-SSP1 – Sustainability – Taking the green road

Texas is characterized by high growth in GDP throughout the 21st century due to strong upward trends in population, urbanization and globalization. Growth in state consumption is increasingly attributed to the use of low material- and energy-intensive products associated with sustainable supply chains and reduced environmental externalities. Civil society undergoes a transformational change toward consumptive behavior that emphasizes sustainable goods and services that capitalize on innovation and enterprises in the state. Large public and private investments in research and development allow the state to benefit from rapid innovation and technological advancements. State urbanization is focused on vertical development in existing urban centers and pan-urban areas including increased use of marginal and under-utilized land. Investments are made in ecosystem restoration and afforestation for carbon sequestration. An increase in the skilled workforce increases per capita incomes and income equality while stronger social policies are adopted that help marginalized and disadvantaged populations. Greenhouse gas emissions are significantly reduced due to a shift away from fossil fuels toward greener and sustainable energy alternatives. These trends also lead to reduced energy demand and externalities of energy including reduced water consumption and improved air quality. Investments in the sustainable management of available water resources increase reliability despite climatic variability. Increasing water use efficiencies across all sectors reduces water demand, consumption, and losses. Water prices for consumers remain stable enabling equitable access, and water quality remains high.

State-SSP2 – Middle of the road

Texas experiences moderate rates of growth in GDP throughout the 21st century due to a rapid increase in population, employment, focus on alternative energy sources and efficient industrial processes. Increasing dependency on natural gas and alternative energy resources helps constrain emissions to moderate to high levels. Stringent federal, state and local regulations around building codes and product standards enable efficiency gains, lower externalities of urban sprawl and drive additional investments in renewable energy resources. The relatively low cost of living and high quality of life attracts people to the state, increasing both international and local migration. Regional and state investments in technology research and development and rates of technological change contribute to increasing regional efficiency and reduced carbon intensity of economic activity. The state land use trends are dominated by high rates of urbanization with significant urban sprawl around existing urban centers. Environmental consciousness leads to retrofitting processes with greener

alternatives, efficient low energy buildings and modest ecosystem restorations. The region experiences continued disparity in income and wealth between skilled and unskilled workers particularly, between urban and rural populations. The private sector seeks to respond to market opportunities created by consumer demand while civil society continues to play an important role in driving the pace of economic growth and technological change through patterns of consumption and demand for goods and services. Energy demand is concentrated in residential and the industrial sectors whereas energy supply is increasingly comprised of clean coal and natural gas facilities with modest gains in renewables such as wind and solar power. Increased demand, competition, and privatization of water resources drive up the water withdrawals, which are offset by incremental improvements in water supply infrastructure.

State-SSP3 – Regional Rivalry – A Rocky Road

Texas experiences low rates of growth in GDP due to global economic headwinds that contribute to low levels of technological development, employment, resource use and consumption. Production largely depends on the competitive advantages between sub-regions and the consumptive patterns are characterized by the use of local and regional resources derived from community-based production. Investments in research and development are highly constrained and thus technological innovation and change is limited to autonomous and incremental improvements of existing technologies. Due to slow efficiency improvements in processes, products and services, Texas struggles to compete technologically with other U.S. states. Land use change is modest due to limited growth and the continuation of existing settlement patterns. Additional land area is brought under cultivation to allow for growth in local farming and crop switching to enhance regional food self-sufficiency. Regional economic headwinds reduce resources and incentives for environmental conservation. Wealth is concentrated in a privileged few hands that disproportionately benefit from regional economic activity. Reduced industrial activity, slow economic growth and low fossil fuel consumption leads to low emissions. State and local governments are weak and poorly resourced. Civil society is focused on identifying local solutions with minimal support from formal government institutions including self-organization to address key concerns of marginalized populations. Energy costs rise due to depreciation of existing infrastructure and limited opportunities to connect to national energy markets and inter-regional energy networks. Regional economic conditions preclude significant investments in water infrastructure whereas demand for water continues to increase modestly across sectors, in part due to lack of progress in demand management and efficiency improvements.

State-SSP5 – Fossil-fueled development – Taking the highway

The GDP of Texas expands at an exponential rate over the 21st century due to rapid growth in population, urbanization, resource use and technological development leading to higher levels of production and consumption of goods and services. Consumption increases rapidly with an emphasis on maintaining low cost products by the efficient exploitation of available resources. Technological innovation is used to offset the externalities associated with intensification of consumption, increasing resource use, and urban sprawl. High rates of population growth and urbanization drive rapid land use conversion and increased pressure on public and private agricultural and forested lands that are not protected, thus contributing to degradation of biodiversity, reduced ecosystem resilience and increased greenhouse gas emissions. Government institutions prioritize maximization of economic development including policies to incentivize business development and extra-regional trade. The private sector leads investments in research and development, human capital, and infrastructure in order to maximize economic gains and to meet the need for efficient, robust, and resilient infrastructure systems to enable commerce. Civil society provides a leading voice for environmental conscientiousness and greening of conventional energy processes as a counter to government and the private sector that focus on maximization of economic growth. Energy demand increases due to rapid population growth and economic development with the supply largely dependent on coal, oil and natural gas as technological advances enable increased exploitation of non-conventional fossil fuel resources. Population growth and economic development drive intensive investments in water resources management including infrastructure to augment supply and water markets to drive water consumption to its most productive use.

Appendix 3.2 – Shared Policy Assumptions Narratives

SPA1 – For hydraulic fracturing in Texas, a high percentage of water is taken from recycled sources, and all of the produced water is desalinated for reuse. The energy for transportation and desalination is derived from wind farms in Texas. Greenhouse gas emissions and other environmental externalities associated with fracking are lowered due to a strong regulatory framework to address the social and environmental aspects of the technology. Federal legislation around decarbonization creates an economy more dependent on renewable energy resources, which targets reductions in greenhouse gas emissions. The state of Texas responds by deregulation of wholesale and retail electricity markets so that renewable resources can compete. A renewable portfolio standard requires retail utilities to provide an increasing volume of electricity from renewable sources over the next few decades. Statewide improvement of transmission infrastructure allows electricity from renewable sources to be transmitted easily through the grid. Federal and state level tax credits are offered to producers of renewable energy, helping them stay competitive against natural gas. A severance tax on the quantity of water consumed in the production of shale gas process mandates oil and gas extracting companies to invest in recycling and desalination technologies. Tax credits on the use of renewable energy resources, for transportation and wastewater treatment, helps lower operational costs of natural gas producers. Information disclosure policies mandate toxic release inventories to be shared about chemicals used in the fracking process. Violators are charged heavy environmental taxes.

SPA2 – For hydraulic fracturing in Texas, equal quantities of water are taken from surface and groundwater for drilling and fracking purposes whereas most of the produced water is deep well injected. No regulation requires reporting of water sources for fracking purposes. Deep well injection of produced water from fracking is regulated under the Safe Drinking Water Act's Underground Injection Control (UIC) program. It also safeguards public health by preventing injection wells from contaminating underground sources of drinking water. The Clean Water Act effluent guidelines program sets national standards for industrial wastewater discharges to surface waters and municipal sewage treatment plants based on the performance of treatment and control technologies. Texas relies equally on surface and groundwater for fracking activities and also has a large network of saltwater aquifers that comply with the UIC program, making it lucrative to use this method for produced water disposal over others.

SPA3 – For hydraulic fracturing in Texas, a significant share of input water is derived from recycled sources, and the rest is made up of equal parts from surface and groundwater for drilling and fracking purposes. Roughly half the produced water is deep well injected, while the rest is desalinated. Natural gas

remains the major source of energy in Texas with fracking activities on the rise. As water resources must be conserved for competing uses, state legislation limits the use of water for fracking activities resulting in a cap and trade program where water disposal via deep well injection rights are traded in the market. Some drilling companies prefer to recycle and reuse water to avoid paying heavy impact fee to the state government. Drilling companies have invested in setting up desalination plants to meet some of their water needs. Some state level subsidies are also in place to help the private sector make such investments in water treatment infrastructure. Others, who manage to secure enough permits, use a large network of saltwater aquifers for deep well injection, which complies with the government standards for safe disposal.

SPA5 – For hydraulic fracturing in Texas, a high percentage of water is taken from recycled sources, and all of the produced water is desalinated for reuse. Transportation uses diesel, while desalination process sources energy from combined-cycle power plants. Natural gas continues to be the major source of energy in Texas with fracking activities on the rise. Federal and state level subsidies and public private partnerships help build new and improved wastewater treatment and desalination facilities to meet the needs of growing energy and water demand. A severance tax on the quantity of water used and disposed of in the production of shale gas limits the water used in the production process. Limits on water use drive oil and gas extracting companies to use recycled water for fracking and use desalination technologies as the primary technology for produced water treatment. Diesel remains the preferred fuel for use in transportation of water to and from the wells.

Appendix 3.3 – Tables and Figures

Table 3.1. Process Water Input and Output for each SSP

Scenario			Percentage (%)	Water (Ml)	Notes	Source (Reference)
SSP 1 Carbon neutral desalination	Input Water	Total	100	35	Business as usual water input quantity (9,326,693 (gal/well))	Clark et al., 2011 Clark et al., 2012
		Surface water[7]	11	4	Percentages based on total desalinated water available	
		Groundwater[2]	11	4	Equal split between surface and ground	EPA, 2015
		Recycled	78	27	All desalinated produced water is reused	
	Output Water	Total Produced water[8]	100	34	Business as usual output quantity (9,057,000 (gal/well))	Clark et al., 2011; Mantell, 2011
		Desalination	80	27	Assuming all produced water is desalinated/reused	Alleman, 2011
		Reject water (Consumption)	20	6.9		Alleman, 2011
SSP 2 Complete underground injection	Input Water	Total	100	35	No recycled water used	Clark et al., 2011 Clark et al., 2012
		Surface water	50	18	Equal split between surface & groundwater	EPA, 2015
		Groundwater	50	18		EPA, 2015
	Output Water	Total produced water	100	34	Business as usual	
		Deep well injection (Consumption)[9]	100	34	Assuming all produced water is deep well injected and consumed	
SSP 3 Partial desalination and partial injection	Input Water	Total	100	35	Business as usual	

[7] The percentages of water sourced from surface water and ground water vary based on studies. According to Nicot et al. 2012, the percentages are surface water (33%) and ground water (60%) whereas EPA (2015) suggests that the percentages are surface water (47.5%) and ground water (47.5%).
[8] Total produced water = produced water + flow back water
[9] Consumption = water that is no longer available to local water users (humans and ecosystems)

Table 3.1 Continued

			Percentage (%)	Water (Ml)	Notes	Source (Reference)
		Surface water[10]	31	11	Percentages based on total desalinated water available	
		Groundwater[5]	31	11	Equal split between surface and ground	EPA, 2015
		Recycled and reused after desalination	38	14	All desalinated produced water is reused	
	Output Water	Total produced water	100	34	Business as usual	
		Desalination	40	14	Only 80% of desalinated water is available for reuse	Alleman, 2011
		Reject water (consumption)	10	3.4	20% of the water is consumed in the desalination process	Alleman, 2011
		Deep well injection (50%) (Consumption)	50	17	Assuming that 50% of produced water is deep well injected and consumed	
SSP 4 Complete desalination & reuse	Input Water	Total	100	35	Business as usual	
		Surface water	11	4	Percentages based on total desalinated water available	
		Groundwater	11	4	Equal split between surface and ground	EPA, 2015
		Recycled	78	27	All desalinated produced water is reused	
	Output Water	Total produced water	100	34	Business as usual	
		Desalination	80	27	Only 80% of desalinated water is available for reuse	Alleman, 2011
		Reject water (consumption)	20	6.9	20% of the water is consumed in the desalination process	Alleman, 2011

[10] This scenario assumes that half of the produced water is desalinated and reused, the input water percentages from ground and surface are calculated over and above the recycled water available from desalination from a previous cycle.

Table 3.2. Energy and diesel inputs under each scenario

		Amount	Units	Source (Reference)
SSP1	Volume desalinated (100%)	$3.43x10^7$	L/well	Assumption
Carbon neutral desalination	Volume desalination output (80%)	$2.74x10^7$	L	Alleman, 2011
	Volume of reject water (20%)	$6.86x10^6$	L	Alleman, 2011
	Diesel to desalination plant	$1.07x10^5$	L	Calculated
	Diesel to fracturing site	$8.55x10^4$	L	Calculated
	Diesel to disposal well (reject water)	$4.27x10^3$	L	Calculated
	Energy for desalination	$5.52x10^5$	kwh	Calculated
	Total diesel used in SSP 1	$1.97x10^5$	L	Calculated
SSP 2	Produced water	$3.43x10^7$	L/well	Clark et al., 2011; Mantell et al., 2011
Complete underground injection	Volume deep well injected	$3.43x10^7$	L/well	Assumption
	Number of trucks	1,647	#	Calculated
	Distance to transport fluid to disposal well	10	Miles	Clark et al., 2011
	Total diesel used in SSP 2	$2.14x10^4$	L	Calculated
SSP 3	Produced water	$3.43x10^7$	L/well	Clark et al., 2011; Mantell et al., 2011
Partial desalination &	Volume desalinated (50%)	$1.71x10^7$	L	Assumption
	Volume desalination output (40%)	$1.37x10^7$	L	Alleman, 2011
	Distance to transport fluid to plant and back	100	Miles	Nicot et al., 2006
	Diesel to transport water to plant	$5.35x10^4$	L	Calculated
	Diesel to transport water to site	$4.28x10^4$	L	Calculated
	Energy for desalination	0.23	kwh/L	Thiel et al. 2015
	Total energy requirement	$2.76x10^5$	kwh	Calculated
	Volume of reject water (10%)	$3.43x10^6$	L	Alleman, 2011
	Diesel to disposal well (reject water)	$2.14x10^3$	L	Calculated
Partial injection	Volume deep well injected (50%)	$1.72x10^7$	L	Assumption
	Diesel to disposal well	2,825	L	Calculated
	Total diesel used in SSP 3	$1.09x10^5$	L	Calculated
SSP 5	Produced water	$3.43x10^7$	L/well	Clark et al., 2011; Mantell et al., 2011
Complete desalination and reuse	Volume desalinated (100%)	$3.43x10^7$	L/well	Assumption

Table 3.2 Continued

		Amount	Units	Source (Reference)
	Volume desalination output (80%)	$2.74x10^7$	L	Alleman, 2011
	Volume of reject water (20%)	$6.86x10^6$	L	Alleman, 2011
	Diesel to desalination plant	$1.07x10^5$	L	Calculated
	Diesel to fracturing site	$8.55x10^4$	L	Calculated
	Diesel to disposal well (reject water)	$4.27x10^3$	L	Calculated
	Energy for desalination	$5.52x10^5$	kwh	Calculated
	Total diesel used in SSP 5	$1.97x10^5$	L	Calculated

Table 3.3. Scenario-Policy Matrix for Fracking in Texas

Socioeconomic Pathways	Technology Choices	Policy Assumptions (summarized - see Appendix B for details)	LCA Model Parameters
SSP1 Sustainability (low challenges for mitigation and adaptation)	**Carbon Neutral Desalination -** A high percentage of water is taken from recycled sources, and all of the produced water is desalinated for reuse. The energy for transportation and desalination is derived from wind power in Texas.	-Strong regulatory system lowers environmental externalities of fracking -Dependency on renewable energy through renewable portfolio standards and state level tax credits -Severance tax on water use promotes conservation -Tax credits on use of renewable energy -Information disclosure policies	**Total Input water:** 9,326,693 (gal/well) Surface water: 1,040,547 (11%) Groundwater: 1,040,547 (11%) Recycled: 7,245,600 (78%) **Total Produced water:** 9,057,000 (gal/well) Desalinated: 7,245,600 (80%) Consumed: 1,811,400 (20%) **Energy Mix:** Renewable sources
SSP2 Middle of the Road (intermediate challenges)	**Complete Underground Injection -** Equal quantities of water are taken from surface and groundwater for drilling and fracking purposes whereas most of the produced water is deep well injected.	-Lack of state regulation around fracking -No limits on water use in fracking -Deep well injection controlled by Safe Drinking Water Act -Deep well injection into Class II wells (EPA approved) -Reuse and recycling of water is voluntary	**Total Input water:** 9,326,693 (gal/well) Surface water: 4,430,179 (47.5%) Groundwater: 4,430,179 (47.5%) Recycled: 466334.65 (5%) **Total Produced water:** 9,057,000 (gal/well) Injected: 8,604,150 (95%) Recycled: 452,850 (5%) **Energy Mix:** Current energy mix
SSP3 Regional Rivalry (high challenges)	**Partial Desalination and Partial Injection –** A significant share of input water is derived from recycled sources, and the rest is made up of equal parts from surface and groundwater for drilling and fracking purposes. Roughly half the produced water is deep well injected, while the rest is desalinated.	-High dependency on natural gas for energy -State legislation limits water use via heavy impact fee -Cap and trade of water rights to disposal wells -State level subsidies for water infrastructure -Decentralized regulatory system with multiple authorities overseeing water management	**Total Input water:** 9,326,693 (gal/well) Surface water: 2,851,947 (31%) Groundwater: 2,851,947 (31%) Recycled: 3,622,800 (38%) **Total Produced water:** 9,057,000 (gal/well) Desalinated: 3,622,800 (80%) Injected: 4,528,500 (50%) Consumed: 905,700 (20%) **Energy Mix:** Predominantly fossil fuels

Table 3.3 Continued

Socioeconomic Pathways	Technology Choices	Policy Assumptions (summarized - see Appendix B for details)	LCA Model Parameters
SSP5 Fossil Fueled Development (mitigation challenges dominate)	**Complete Desalination and Reuse -** A high percentage of water is taken from recycled sources, and all of the produced water is desalinated for reuse. Transportation uses diesel, while desalination process sources energy from combined-cycle power plants.	-Investment in wastewater treatment infrastructure and desalination plants through federal and state level subsidies and public private partnerships -Severance tax on water use promotes reuse and recycling of water for fracking	**Total Input water:** 9,326,693 (gal/well) Surface water: 1,040,547 (11%) Groundwater: 1,040,547 (11%) Recycled: 7,245,600 (78%) **Total Produced water:** 9,057,000 (gal/well) Desalinated: 7,245,600 (80%) Consumed: 1,811,400 (20%) **Energy Mix:** Fossil fuel intensive

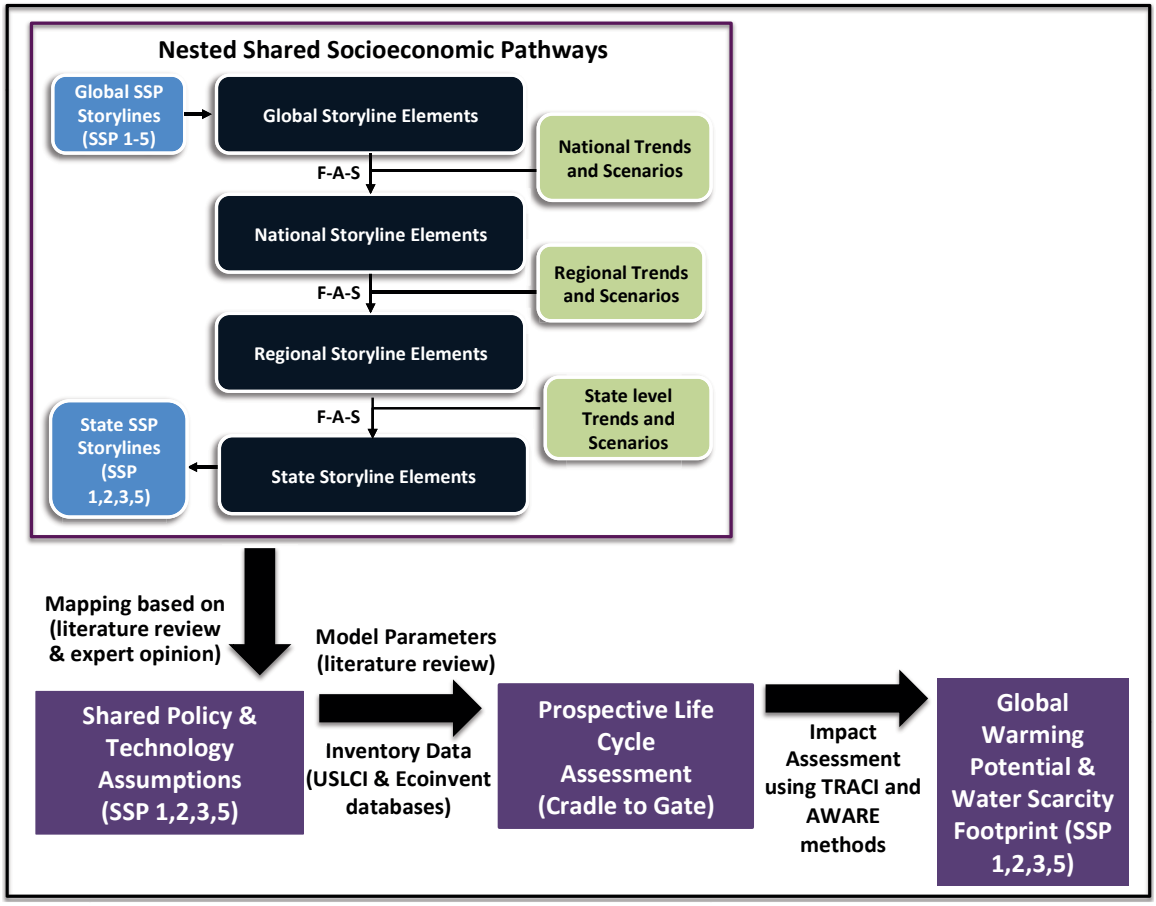

Figure 12. Prospective Life Cycle Assessment Conceptual Model

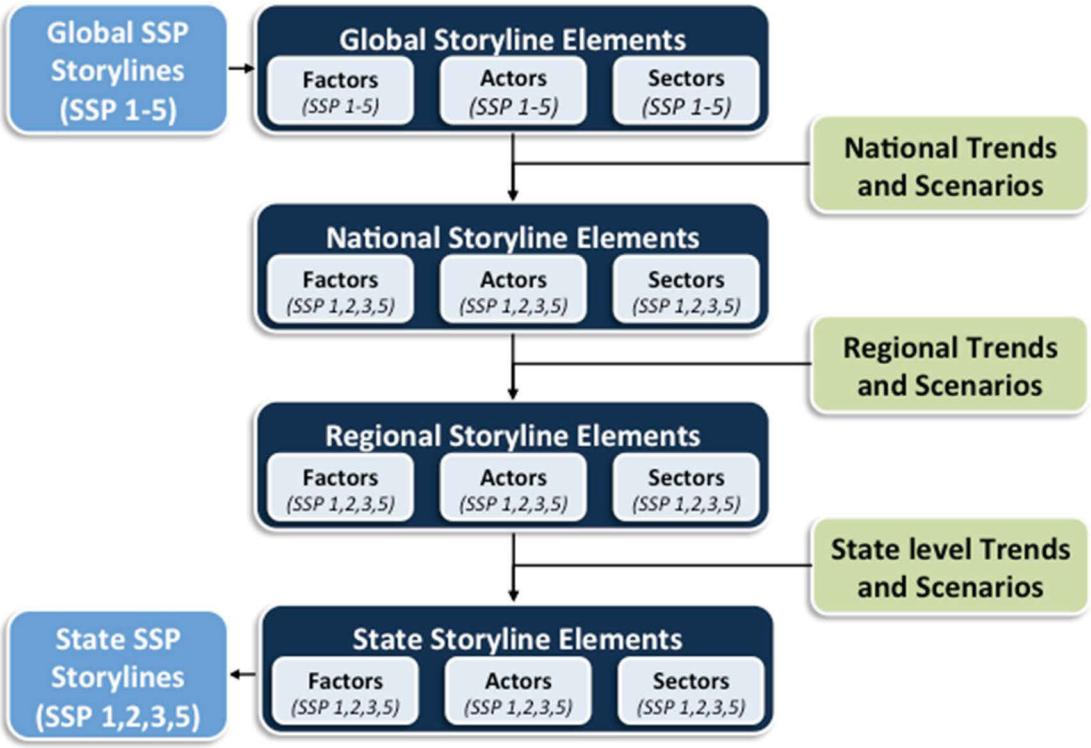

Figure 13. Illustration of SSP storyline nesting from global to local scale, based on Factor-Actor-Sector framework, adapted from Absar & Preston (2015).

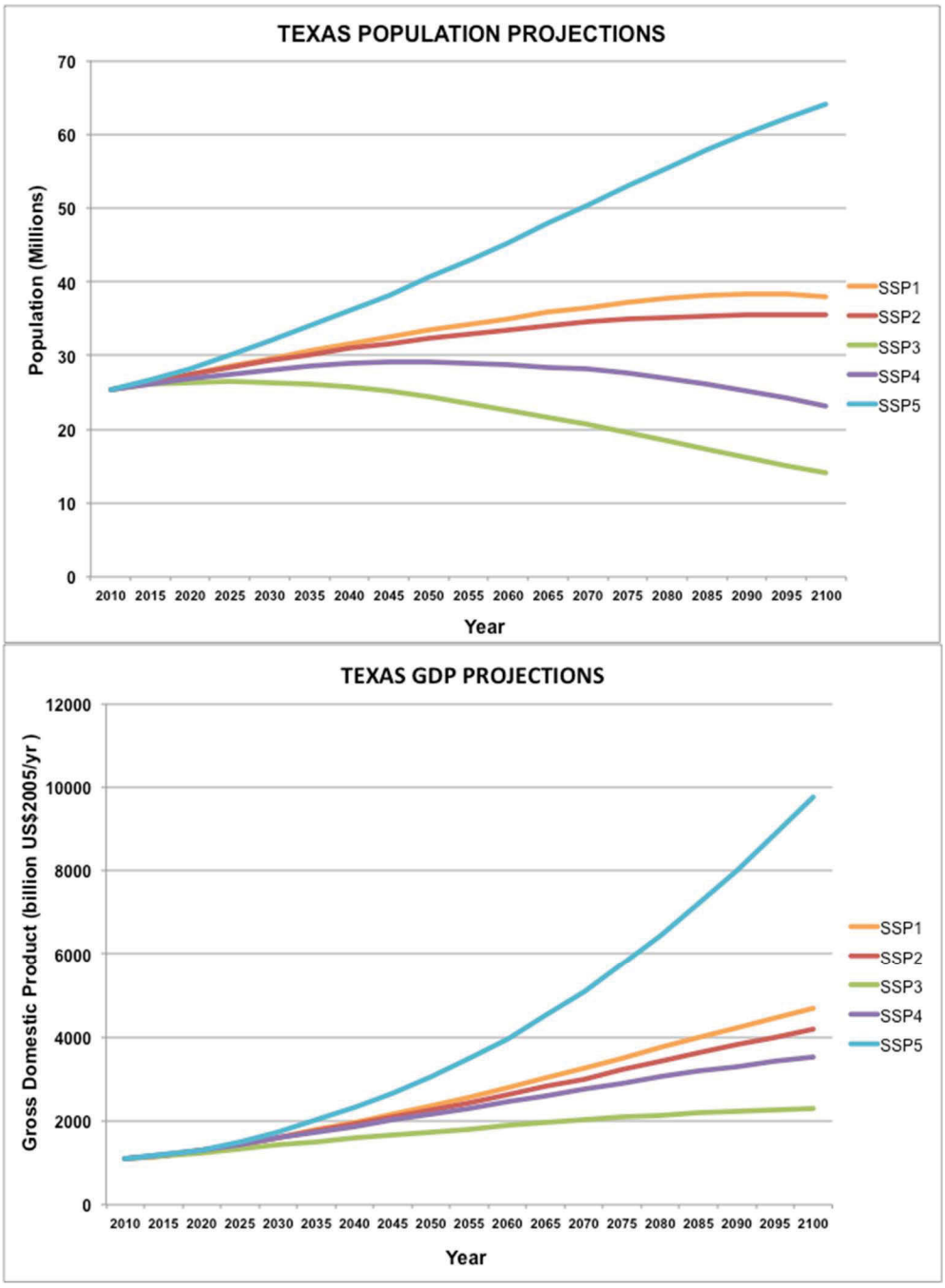

Figure 14. Quantitative population and GDP scenarios for Texas based on four different global SSP boundary conditions.

Population and GDP scenarios were derived by applying county-level scaling factors to national population and GDP estimates within the IIASA database (IIASA, 2012). Population scaling factors were based on the proportion of total U.S. population change attributed to individual counties as indicated by the ICLUS population scenarios (2010–2100). GDP scaling factors were based on the historical (1997–2011) average proportion of U.S. GDP attributed to Texas considered in the current study.

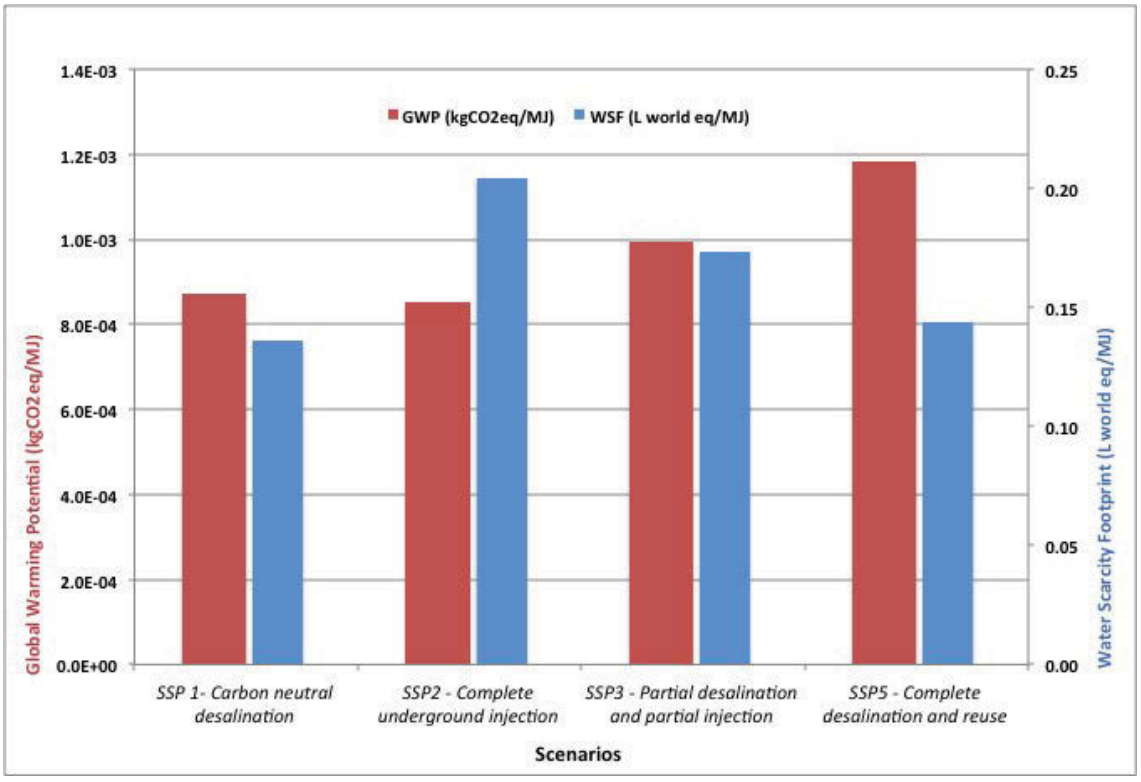

Figure 15. Global Warming Potential and Water Scarcity Footprint using the nested shared socioeconomic pathways and life cycle assessment model developed by Absar et al. (2017, submitted).

Conclusion

The United States is the world's largest consumer of natural gas and with the breakthrough in shale gas extraction technology; the U.S. has doubled its natural gas production in the last 6 years (Kobek et al., 2015). According to the Energy Information administration, the current recoverable resource estimate of 750 trillion cubic feet of shale gas resource provides enough natural gas to supply the U.S. for the next 90 years (EIA, 2011). New natural gas developments bring change to the environmental and socioeconomic landscape. Due to the nature of shale gas development, questions arise about the potential environmental impacts of this activity and the ability of the current regulatory structure to deal with this industry especially in the long run when faced with stressors such as climate change which is already causing severe drought conditions in parts of the country heavily producing shale gas such as Texas (Roy et al., 2012). Policy-makers need a reliable source to base answers to these questions and decisions about how to manage the challenges that may accompany shale gas development as this industry moves into the future (GWPC, 2009). Due to limited published literature around climate change and impacts on energy-water nexus in fracking (Scott et al., 2011) particularly in the drought prone regions of the country, this dissertation took an in-depth look into understanding the complexity of this nexus with a particular focus on the Barnett shale play in Texas, and its adaptation to climate change.

Chapter 1 of this dissertation developed sub-national and sectoral extensions of the global SSP storylines in order to identify future socioeconomic challenges for adaptation for the U.S. Southeast. A set of nested qualitative socioeconomic storyline elements, integrated storylines, and accompanying quantitative indicators were developed through an application of the Factor-Actor-Sector framework (Kok et al., 2006a). This study generated sub-national storylines that can subsequently be used to explore the implications of alternative sub-national socioeconomic futures for the assessment of climate change impacts and adaptation (Absar et al, 2017, forthcoming, see Chapter 3). Further research is required to test these storylines in various modeling environments and applications to local impacts, adaptation and vulnerability studies. The storylines are based on normative judgments of the developers, multiple instances of these storylines need to be developed and tested for different assessment goals, in disparate contexts and for comparison across different fields of study while still maintaining their internal consistency with the global SSPs. In addition, participatory scenario development techniques can be used to develop bottom up scenarios around specific local domains of interest (Birkmann et al., 2013; Kok et al., 2006a,b) and then if relevant, linked to conditions and trends at more global scales (Holman et al., 2005; Sleeter et al., 2012) for more detailed and context specific qualitative storylines.

Chapter 2 takes an in-depth look at the energy water nexus in the context of hydraulic fracturing in a drought prone and natural gas rich region of Texas. Globally, the oil and gas industry uses far less water than agriculture or power generation, though it can be a significant user of water at the local level. Shale gas production is a water intensive process. As climate change affects the availability of water resources, so do other stressors like urban population growth, economic development, and thus increase the withdrawals occurring in the watersheds already experiencing scarcity. To understand the use of energy and water in a typical shale well in Barnett, Texas, a life cycle assessment model was developed to quantify the global warming potential and the water scarcity footprint of 1 MJ of shale gas produced for multiple instances of wastewater management. The resulting tradeoffs of energy and water use highlight the need for informed policy and effective regulation for sustainable evolution of this industry into the future. This model is effective in comparing discrete scenarios around wastewater management or any other aspect of an energy system and for testing various policy levers to orient the process toward a desired outcome (see Chapter 3). This investigation into the sustainability of hydraulic fracturing in Barnett, Texas serves as a case study to improve understanding of energy systems and the inherent tradeoffs between energy and water to better understand and manage the energy water nexus on a local scale.

Chapter 3 draws upon the modeling frameworks developed in Chapters 1 and 2 and combines them to evaluate the future of the energy water nexus in Texas by testing various policy levers that can help optimize energy and water use in the hydraulic fracturing industry. The nested state-level SSPs for Texas provide a flexible tool to explore the uncertainty associated with the evolution of technology pathways and their implications for the pursuit of climate-resilient fracking operations. When combined with a prospective life cycle assessment model for fracking, this framework also allows technology choices to be quantified to understand tradeoffs related to resource use. The results from the LCA for different SSPs indicate that a system that has higher carbon footprint has a lower water footprint and vice versa (Mekonnen et al., 2016). Such trade-offs pose challenges for setting priorities for overall environmental improvement, as it may not be possible to minimize both water consumption and energy consumption unless a conducive policy environment was created to do both. Given the trade-offs inherent in the management of wastewater from fracking, the integration of scenarios with LCA is the identification of decision points that can transition fracking from one technology pathway to another. This enables decision-makers to avoid path-dependence that can lock the industry into long-term decisions that can undermine efforts to adapt to the changing climate (Ernst & Preston, 2017; Preston, 2013).

Future work involves using this framework as a decision making tool by the fracking industry and/or policy makers. The industry can test the impact of new technologies and assess investment options based on the energy-water tradeoff. The policy makers can scale up the environmental impacts from the greenhouse gas emissions and water consumption in hydraulic fracturing practices for the entire Barnett Shale play or the state, from introducing specific policies. The industry and policy makers can also combine this tool with a life cycle cost analysis (LCCA) tool to determine the cost of investing in a technology or implementing a policy. One such LCCA model is the EPA's Integrated Decision Support Tool (i-DST), which has an LCA model called Water-Energy Sustainability Tool (WEST), integrated into it. This tool is used for optimization, uncertainty assessment, and life cycle cost assessment (LCCA) of grey, green, and hybrid storm-water infrastructure on a site or a sewer-shed scale. Such a tool can also help carry out a multi-criteria decision analysis and optimization across energy, environment and cost tradeoffs.

Introducing geospatial data and scenarios around increase or decrease in the number of wells drilled, changes in population and urbanization, different energy mixes, water availability due to climate change and competition from other users, combined with LCA results can further enhance the understanding and planning for the sustainability of energy-water nexus in Texas. A GIS- based regionalized LCA can be designed using this tool as the core model. Similar work has been done by Mutel et al. (2012) and Liu et al. (2014) where GIS can allocate the environmental impacts into smaller spatial units through the overlay analysis of fate, exposure and effect layers.

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Vita

Mariya Absar was born and raised in Islamabad, Pakistan. She received the Fulbright Scholarship, which brought her to the United States in 2006, to pursue her graduate studies at Yale University, in Environmental Management. Mariya is passionate about the environment and has ten years of experience researching climate change impacts and adaptation of the energy, water and land nexus. Her most recent affiliation has been with the Oak Ridge National Laboratory (ORNL) where she started as a Post-Masters researcher in 2012, in the Computer Science and Mathematics Division then transitioned to the Environmental Sciences Division before starting her PhD with the University of Tennessee, Knoxville in Energy Science and Engineering. Her experience at ORNL has taught her many skills such as crop modeling using climate model data, socioeconomic scenarios development, life cycle assessment, optimization and geographical Informational System to name a few. Mariya loves to travel and has been to 19 countries. She lives with her husband Sam and daughter Nora in Knoxville, Tennessee.

Mariya received her primary education in Islamabad then spent 5 years in Egypt as a military-diplomat's kid studying at an International school with the children of other diplomats from all over the world. Upon her return to Pakistan, she completed her high school certification from Cambridge University, UK in 1999 through an external program offered by most private schools in Pakistan. She took a gap year after high school to attend a Finishing School in Islamabad and graduated a valedictorian. She started college at the Lahore University of Management Sciences, in 2000 as a Computer Science Major and upon graduation in 2004, she started working at the National Commission for Human Development on a digital literacy project funded by Microsoft Corporation to set up computer learning centers in the rural parts of Pakistan.

After graduating from Yale in 2009, Mariya started working as a Water Policy Analyst in her hometown of Islamabad, researching effective water policy instruments for Pakistan and other developing countries. One of these studies was published in the Journal of Future Studies and received the Jan Lee Martin Best Article Award in 2013. Mariya also worked as a visiting researcher at the International Institute for Applied Systems Analysis (IIASA) through their Young Scientists Summer Program in 2011 where she analyzed the returns on investment in water saving irrigation options, for farmers in Punjab, Pakistan, and published it as IIASA's Interim Report. This work was an extension of her Master's thesis at Yale University with Professor Robert Mendelsohn wherein she developed a production and demand function for farmers in water stressed Punjab using econometric analysis. After IIASA, she briefly worked at Yale University on an Online Access to Research in the Environment (OARE) Project before moving to ORNL.