THE SUSTAINABLE WATER-ENERGY NEXUS: LIFE-CYCLE IMPACTS AND FEASIBILITY OF REGIONAL ENERGY AND WATER SUPPLY SCENARIOS

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B.S. in Engineering Physics, University of Pittsburgh, 2009

Submitted to the Graduate Faculty of

the Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2013

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

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Water and energy are critical, interdependent, and regional resources, and effective planning and policies around which sources to use requires combining information on environmental impacts, cost, and availability. Questions around shifting energy and water sources towards more renewable options, as well as the potential role of natural gas from shale formations are under intense discussion. Decisions on these issues will be made in the shadow of climate change, which will both impact and be impacted by energy and water supplies.

This work developed a model for calculating the life-cycle environmental impacts of regional energy and water supply scenarios (REWSS). The model was used to discuss future energy pathways in Pennsylvania, future electricity impacts in Brazil, and future water pathways in Arizona. To examine energy in Pennsylvania, this work also developed the first process-based life-cycle assessment (LCA) of shale gas, focusing on greenhouse gas (GHG) emissions, energy consumption, and water consumption. This LCA confirmed results that shale gas is similar to conventional gas in GHG emissions, though potentially has a lower net energy due to a wide range of production rates for wells.

Brazil's electricity-related impacts will rise as development continues. GHG emissions are shown to double by 2020 due to expanded natural gas (NG) and coal usage, with a rise of

390% by 2040 posssible with tropical hydropower reservoirs. While uncertainty around reservoir impacts is large, Brazil's low GHG emissions intensity and future carbon emissions targets are threatened by likely electricity scenarios.

Pennsylvania's energy-related impacts are likely to hinge on whether NG is used as a replacement for coal, allowing GHG emissions to drop and then plateau at 93% of 2010 values; or as a transition fuel to expanded renewable energy sources, showing a steady decrease to 86% in 2035. Increased use of biofuels will dominate land occupation and may dominate water consumption impacts, depending on irrigation – water consumption for energy rises from 7% to 18% under the base case.

Arizona is further from major shale basins, but aims to reduce unsustainable groundwater usage. Desalination by itself will increase annual impacts by at least 2% in all impact categories by 2035, and prioritizing renewable energy sources along with desalination was found to lower GHGs by 1% from BAU, but increase 2035 impacts in all other categories by at least 10% from new construction or operation.

In both PA and AZ, changes in impacts and shifting sources have interconnected tradeoffs, making the water-enegy nexus a key part of managing environmental problems such as climate change. Future energy and water supplies are also likely to show higher interdependencies, which may or may not improve regional sustainability. This work offers a way to combine four important sets of information to enable the generation of answers to key regional planning questions around these two key resources.

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NOMENCLATURE

AEO	Annual Energy Outlook (EIA Publication)
AEP	Alternative Energy Portfolio (Energy policy)
ANEEL	Brazilian Electrical Energy Agency (Agéncia Nacional Energia Elétrica)
AZ	Arizona
BAU	Business as Usual
BCF	Billion Cubic Feet
BR	Brazil
BTU	British Thermal Unit
CAP	Central Arizona Project
CED	Cumulative Energy Demand
CF	Capacity Factor
CWNS	Clean Watersheds Needs Survey
DOE	United States Department of Energy
EfW	Energy used for water supply
EIA	United States Energy Information Administration
LfW	Electricity used for water supply
EPA	United States Environmental Protection Agency
EROI	Energy Return on Investment
GHG	Greenhouse Gas

GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Transportation
GWP	Global Warming Potential
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LC	Life-Cycle
LCA	Life-Cycle Assessment
MCA	Monte Carlo Analysis
MCF	Thousand Cubic Feet
NREL	National Renewable Energy Laboratory
PA	Pennsylvania
REWSS	Regional Water and Energy Supply Scenarios (Model)
RPS	Renewable Portfolio Standard (Energy policy)
RFC	Reliability First Corporation
SWEN	Sustainable Water-Energy Nexus
TDS	Total Dissolved Solids
TRACI	Tool for the Reduction and Assessment of Chemical Impacts
US LCI	United States Life-Cycle Inventory (database)
VMT	Vehicle Miles Traveled
WEN	Water-Energy Nexus
WfE	Water consumed for energy supply
WfL	Water consumed for electricity supply

PREFACE

I am deeply grateful to my advisor, Melissa Bilec, who has managed to guide me through a set of research often outside of her normal field. Similar thanks must be given to my dissertation committee for both large and small pushes in a better direction throughout the process.

I must thank the Sustainability and Green Design group for their support on both an academic and social level through my four years here.

And finally, I must dedicate this document to my wife, Amy, who has put up with my late-night work schedule and babbling on about energy and boundary conditions, and has been patient and loving through all of it.

1.0 INTRODUCTION

1.1 THE WATER-ENERGY NEXUS: A NEED FOR COMPREHENSIVE PLANNING

Modern societies rely on high-magnitude, inexpensive, and reliable flows of water and energy. Energy flows, in electricity, transport, and direct heat, support most of the services and activities in modern life including delivery of water. Water is fundamental to life, regardless of modernity, but is also heavily used for irrigation and power generation as well as by many industrial processes. The inherent interdependent relationship between water and energy is known as the Water-Energy Nexus (WEN) [1]. Energy usage in the United States is roughly 28,000 terawatt-hours (TWh) per year [2], and ~5% of US electricity consumption is for water treatment and delivery [1]. Water withdrawals are ~150 trillion gallons annually, 40% of which is used for power generation [3]. Both water and energy have large dedicated infrastructures, and follow similar life-cycles: resource reservoirs provide an initial supply which is extracted and processed, converted or treated, and delivered to final users. Each water or energy source has its own advantages and limitations. Growing demand and limited or diminishing supplies stresses all parts of the WEN: water, energy, water-for-energy, and energy-for-water. Many of the limitations on energy and water resources are regional, as are the applicability and sustainability of new technologies, some of which increase the interdependence between these two resources. Identifying the impacts of supplying energy and water from regional sources and assessing regional stresses and limits going forward is key to making policy decisions about how we use these fundamental resources.

The world's population increases over the last decades have allocated most of its natural resources, particularly those that supply energy or water. Major rivers are now dammed and used for hydropower as well as cooling thermoelectric plants, for drinking water for towns and cities, and for irrigation of food in many areas. These competing uses have left little extraneous supply to be allocated for future growth. At the same time, energy consumption has risen through the use of energy dense and relatively inexpensive fossil fuels – coal, petroleum, and natural gas.

Energy and water have traditionally been managed by separate entities with minimal communication. The need to plan these two resources together because of their independence requires a tool for considering them simultaneously with comparable metrics. While previous work has provided the detailed data on the myriad sources of energy and water, as well as created frameworks for assessing connections between particular systems, there is a lack of an accessible tool for tying together all aspects of energy and water on a regional basis or using life-cycle environmental impacts.

1.2 DEFINING SUSTAINABILITY

Sustainability as a term has risen to prominence, but is often poorly defined. It is also the result of recent marketing over-usage, further requiring explicit definition. The 1987 UN Brundtland Report defined sustainable development [4], but that definition lacks applicable specificity. For the purposes of this work, sustainability is defined as *"Resource usage at or below the natural rate of regeneration,"* a definition based very much on physical processes, which are the focus of this work. This definition applies equally well to resources such as biomass as to natural buffering capacity – climate change is the result of releasing greenhouse gases (GHGs) faster than natural systems can absorb them.

Because we do not live in a sustainable world, it is also worthwhile to define a path towards one. Such a path could be reasonably referred to as sustainable development, and is defined here as "*Decreasing the rate of use of unsustainably procured resources at such a rate that sustainability is reached before the resource is exhausted.*" This definition implies, appropriately, that resources such as natural gas can be part of sustainable development as long as society is focused on reducing total use of them, subject to other constraints such as total GHG emissions. These definitions are difficult to extend to societal aspects such as inequality that are nevertheless part of a more complete definition of sustainability – for an example, see The Natural Step framework [5]. For this work, however, a more specific and quantifiable definition is both appropriate and useful.

1.3 RESEARCH OBJECTIVES

The goals of this research were to investigate the environmental impacts of future energy and water supplies with a life-cycle perspective but regional focus. The two main areas of interest are the shifts to new sources of both energy and water, and the variation between regions under the same general trends of climate change, shale gas development, and decreasing water availability. To investigate these areas, data from life-cycle assessment (LCA) studies and the signficiant amount of existing literature data were combined in a robust tool designed for non-experts, using Monte-Carlo Assessment for uncertainty analysis. This work focused on five impact categories:

global warming potential (GWP), energy consumption, water consumption, land occupation, and economic cost. By assessing business-as-usual (BAU) scenarios and, where appropriate, comparing them with alternatives scenarios, the tradeoffs of using certain technologies and the impacts of regional conditions can inform policy paths going forward. The main objectives of this research were to:

1. Assess energy and water consumption during production of natural gas from the Marcellus Shale and confirm estimates of global warming potential. (Chapter 3)
2. Examine plausible changes in environmental impacts from changes in electricity generation in Brazil over the coming decades. (Chapters 4 & 5)
3. Examine the environmental impacts of shifts in energy and water sources for Arizona and Pennsylvania (Chapters 4 & 6)
4. Develop a tool aimed at non-experts so that others can asssess water and energy supply questions for their own regions with quantitative and holistic support. (Chapter 4)

1.4 INTELLECTUAL MERIT

This work represents the first general model for assessing the impacts of water and energy supplies in a region as a combined system. The simultaneous consideration of water and energy supplies in a consistent framework that is easily adaptable to any region or timespan, combined with the specificity of a process-based – rather than input-ouput – approach, is a novel addition to the field. From a broader perspective, the model is available for download and use by future users, with potential questions and future work discussed in Chapter 7. In order to examine Pennsylvania’s future energy supplies, this work also provides the first estimate of EROI for shale as part of the first fully process-based LCA of natural gas from the Marcellus Shale, focusing on GWP, energy consumption, and water consumption.

The REWSS model developed at the center of this work has the additional benefits of having uncertainty assessment available – though uncertainty is only as good as the distribution data – and considering a broader set of impacts and life-cycle stages than other tools. Although a unique space can always be defined by combining enough terms and areas, water and energy are physically linked, often to a region, while their impacts and sources will extend into the future and are shifting due to new technologies and limits. Combining these terms in an accessible manner can provide new insight into the significant but unexpected impacts from new technologies, as well as negligible effects from other changes.

1.5 BROADER IMPACTS

The general importance of the topics this work addresses – water, energy, policy, region, climate change – is clear from their role in shaping everyday life. The research questions are the source of contentious public debate, particularly around the Marcellus Shale and what energy sources will be used in the next decades. In addition, the goal of the REWSS model is to be available and applicable to non-experts, with periodic data updates using existing published data such that policy questions for any region can be easily explored. This work, as well as several preliminary studies using life-cycle assessment on policy-related energy technologies, takes the form of six peer-reviewed articles are at various stages of publication during the final writing herein:

1. Dale, AT; Bilec, MM; Marriott, J; Hartley, D; Jurgens, C; Zatcoff, E, Preliminary Comparative Life-Cycle Impacts of Streetlight Technology. *Journal of Infrastructure Systems* **2011,** *17*, (4), 193-199.
2. Dale, AT, Green, O, Shatzer, K, Brigham, J, Landis, AE, Bilec, MM, Preliminary Methods in Optimal Design for Minimal Life-Cycle Impacts of Gasoline Blends. *Energy Policy (In Revision)*
3. Dale, AT; Vidic, RD; Khanna, V; Bilec, MM, Process Based Life-Cycle Assessment of Natural Gas from the Marcellus Shale. *Environmental Science & Technology (Under Review)*
4. Dale, AT, Borba, BSMC, Lucena, AFP, Marriott, JM, Schaeffer, R, Bilec, MM, Modeling Future Life-Cycle Environmental Impacts of Electricity Supplies in Brazil. *Energies (Submitted for review)*
5. Dale, AT; Bilec, MM, Tools for Quantitative Long-term Water & Energy Planning, Part I: The Regional Energy & Water Supply Scenarios (REWSS) Model, (In preparation)
6. Dale, AT; Bilec, MM, Tools for Quantitative Long-term Water & Energy Planning, Part II: Applying the REWSS Model to Pennsylvania and Arizona, (In preparation)

This work has been partnered with outreach efforts around the Marcellus Shale and energy and water connections at several conferences and organizations. The primary organizational partner has been Engineers for a Sustainable World (ESW), which this researcher has been working with at the national level throughout the completion of this work. Aspects of this work have been presented at two ESW conferences and informed several national educational events. Locally, presentations and guest lectures in graudate classes have increased awareness of energy and water issues and helped stimulate rational discussion about the use of the Marcellus Shale as part of Pennsylvania’s energy future.

Finally, this work and the funding behind it have been instrumental in building connections between the University of Pittsburgh and the Federal University of Rio de Janeiro in Brazil. This researcher spent the spring semester of 2012 in Rio de Janeiro collaborating with researchers in the Energy Planning Program (Programa de Planejamento de Energia, PPE), and the results of that work make up the fourth chapter of this dissertation and an early use of the REWSS model that is central to this work.

1.6 DOCUMENT STRUCTURE

Chapter 2 provides a background on water, energy, their interconnection, and previous work on modeling future impacts. Information on the Marcellus Shale and the current status of the three case study regions is also included. Chapters 3, 4, and 5 focus on the specific objectives. Chapter 3 presents a process based life-cycle assessment of natural gas extraction from the Marcellus Shale. Chapter 4 presents the central result of this work, a process-based model for integrating energy supplies, water supplies, regional conditions and priorities, and life-cycle impacts that is referred to as the REWSS model. The REWSS model was created as an outcome of this work. Specific approaches for modeling electricity in Brazil and energy & water overall in PA and AZ are also discussed. Chapter 5 presents results from an analysis of future electricity supplies in Brazil, while Chapter 6 presents results from applying the REWSS model to energy & water in Pennsylvania and Arizona. Overall implications of this tool and work, as well as prospects for future work, are discussed in Chapter 7. Collected LCA data and supporting information are available in the Appendices, with Appendix A providing data and assumptions for the Marcellus Shale, Appendix B providing details and built-in information for the calculation model, Appendix C providing additional information for Brazil, and Appendix D providing additional information for scenarios in PA and AZ.

2.0 BACKGROUND AND LITERATURE REVIEW

2.1 OVERVIEW

This work combines data from many different areas, which are shown in Figure 1 and individually described below. Energy and water each have independent sources, and combined form the water-energy nexus (WEN). The regional WEN is influenced not only by regional conditions, but also by large-scale trends such as climate change, water availability, and the rise of unconventional oil and gas development. In considering questions for the future, one common research approach is to use scenario analysis to talk about different possible futures. The outcomes that this work is interested in are the life-cycle impacts of the WEN under those scenarios, and the implications for regional sustainability.

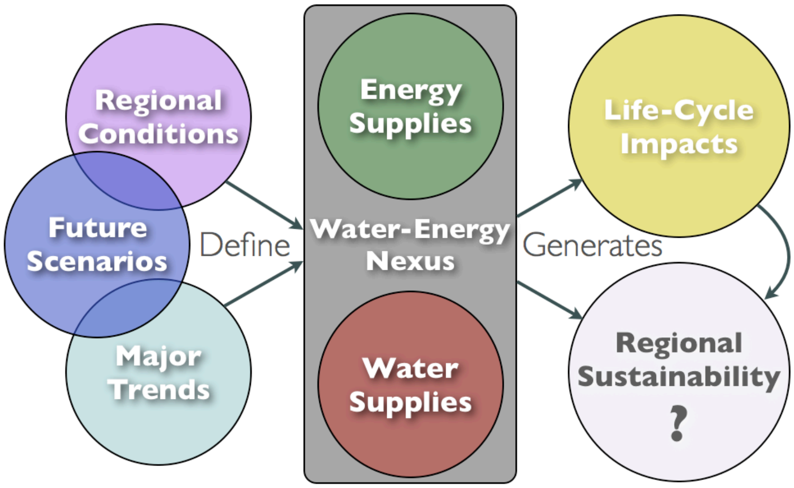

Figure 1: Conceptual connections between the topics addressed in this work

2.2 THE WATER-ENERGY NEXUS

2.2.1 Energy History

The world relies on nine major sources of energy: combustion of coal, oil, natural gas, and biomass, potential energy from falling water, kinetic energy from wind, solar radiation, and heat from nuclear fission and geothermal wells [6]. These energy sources are used to provide three major energy services: Electricity, heat, and transportation. The general supply chain for energy is shown in Figure 2. No energy source is perfect, and the tradeoffs between them vary between physical, political, and economic limitations. The various sources can be compared by common physical metrics including estimated reserves, energy return on investment (EROI), and geographic dependence – whether the source only works in certain areas.

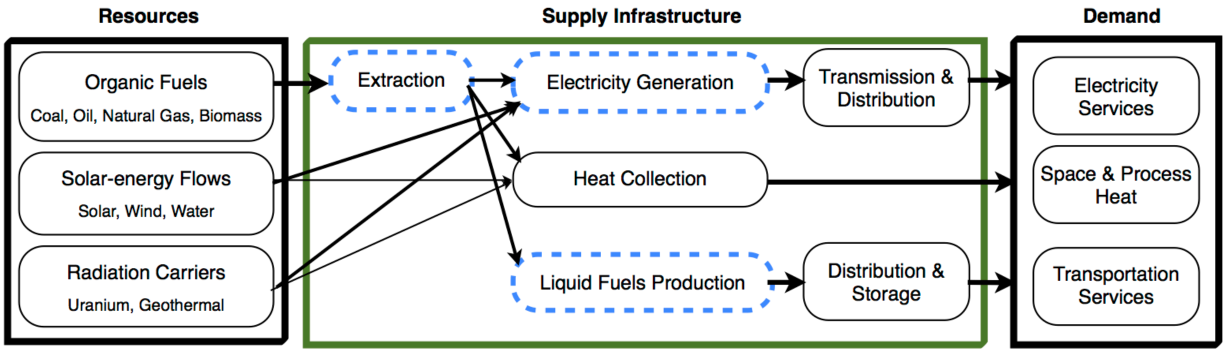

Figure 2: The Energy Supply Chain

Dashed blue borders denote processes with significant water usage.

Energy supply is dominated by the three phases of fossil fuels: coal, oil, and natural gas (NG). Coal provides ~50% of US electricity [7], oil is used for >90% of transportation energy, and natural gas is used to produce 19% of US electricity, 76% of residential and commercial direct heat requirements, and 2% of transportation demands [8]. All three of these fossil energy sources are inexpensive, easy to transport, and are energetically dense. However, all are finite resources, and have significant emissions of carbon dioxide and other pollutants when burned. Newer unconventional sources of oil and gas, such as tar sands and shale gas reserves, require more energy and water during extraction, lowering their EROI and increasing life-cycle impacts [9-11]. The annual form of combustable stored solar energy is biomass, which is used for heating in the US and as a secondary or replacement fuel in fossil fuel plants [12]. Biomass is normally considered to be renewable because the carbon is sequestered very close to when it is released, but overuse can still lead to depletion. Biomass is also used as a feedstock in producing biofuels, producing similar energy densities as petroleum in a final product with a renewable source.

Other renewable sources of electricity include hydro, wind, and solar. Hydroelectricity generates a relatively constant 9% of US electricity, with some flexibility in generation [8]. However, dams can often flood large areas, segregate upstream ecosystems, and result in extra evaporation, though they have secondary perceived or actual benefits such as recreation and water storage. Dam placement is also limited by geography and, in the US, increasing social opposition. Distributed renewables such as photovoltaics and wind turbines collect highly renewable energy flows, but have lower energy density and much higher short-term variability than thermo- or hydroelectric sources. Renewable energy sources are also geographically dependent - wind is not transportable. In terms of a sustainable WEN, the use of renewable sources is critical and the amount of energy captured from renewable energy flows will likely prove the limiting factor on standard of living. While energy consumption from renewable energy sources has grown by 6.8% annually over the last five years, these sources represented only 8% of total energy consumption in 2010 [8].

The final two sources of energy are based on radioactivity - in the form of either fission at nuclear power plants or geological radiation from the Earth's core. Geothermal energy, which is used for both heating and, in certain areas, electricity, is classified as renewable, though any particular location will cool over time. Geothermal's low variability is matched by a high geographic dependence for electricity production. Nuclear power from fission is a much-debated topic relative to other energy sources. While its carbon footprint is significantly lower than those of the fossil fuels [13], its requires more water per unit of output, and has a spate of unique problems including waste management, high initial costs, and high-magnitude, low-incidence accidents [14]. Current barriers to nuclear power are not technical or physical, but economic, and socio-political.

The energy history of the US is shown in Figure 3, dominated by fossil fuels. Moving forward, there is a need to move to more sustainable energy resources. All energy sources have tradeoffs, and the value of quantitative analysis is in determining which tradeoffs are maneagable given regional parameters in order to identify policy paths forward for different regions.

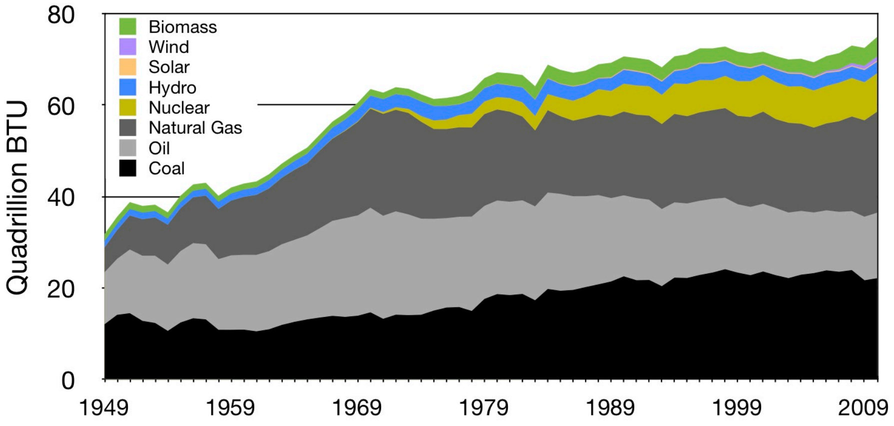

Figure 3: US Energy History by Fuel

Primary energy consumption by fuel, taken from the US EIA [8].

2.2.2 Water History

Freshwater sources are fewer in number than energy sources, with four primary resource types: local surface water, local groundwater, imported water from other watersheds, and desalination of saline sources. The availability of each type is primarily dependent on local climate, with a secondary dependence on infrastructure investments. Water sources are compared in terms of either simple quantity or various measures of quality, often including total dissolved solids as a measure of salinity.

Unlike energy supplies, which have been used and developed in parallel, water sources are often used in a specific order. Local surface freshwater sources are used first, minimizing energy required for pumping and avoiding the need to drill wells [15]. In times of drought, or when it is impractical to transport water far from its source, groundwater sources are used. Groundwater aquifer recharge rates range from effectively immediate to thousands of years, and so some aquifers are deemed ‘fossil’ aquifers in that they can only be used once for practical purposes. Many western and midwestern aquifers fall into this category, making groundwater a necessary but non-renewable source in the current mix.

When local sources combined are insufficient to meet demand, as in much of the southwestern (SW) US, several tactics can be employed: Dams for water storage, inter-watershed conveyance projects, and desalination or wastewater reuse plants. Dams store water to smooth natural variability, but are not a water source – and storage increases evaporation in most cases. Over the course of the 20th century, many watersheds in the SW US have become connected by capital-intensive conveyance projects, some fed primarily by gravity, others actively pumped. These projects allow ‘surplus’ water to be moved to coincide with demand on a limited basis that again increases evaporation as a parasitic cost. These systems have become critical to many SW cities, including Phoenix, AZ and Los Angeles, CA [16]. With the rise of conveyance projects in the SW US and increasing downstream reuse of rivers in the northeastern (NE) US, regional water impacts - to both quality and quantity - affect places outside of a given region. Climate change adds additional stress to water systems in quantity limited regions such as the SW US [17-19], while ecosystem pressures such as excessive nutrients have lead to quality issues in other regions such as the NE US [20].

If water is delivered to a municipal system, it is treated to potable standards, used, and then recollected and treated, occasionally along with stormwater, to regional or plant-specific standards before being discharged into the environment. Water treatment, given water from a generic source, is comprised of a standard set of processes which occur throughout the country, with various aspects such as disinfection method varying by plant. Similarly, wastewater treatment has a relatively standard set of linear processes. Variation in wastewater treatment can occur when policies or permits dictate additional treatment. Advanced treatment can involve the removal of additional contaminants such as nitrogen, phosphorous, and pharmaceuticals, or more advanced treatment of sludge such as in an anaerobic biodigester. The overall supply chain for water, with energy-intensive sections highlighted, is shown in Figure 4.

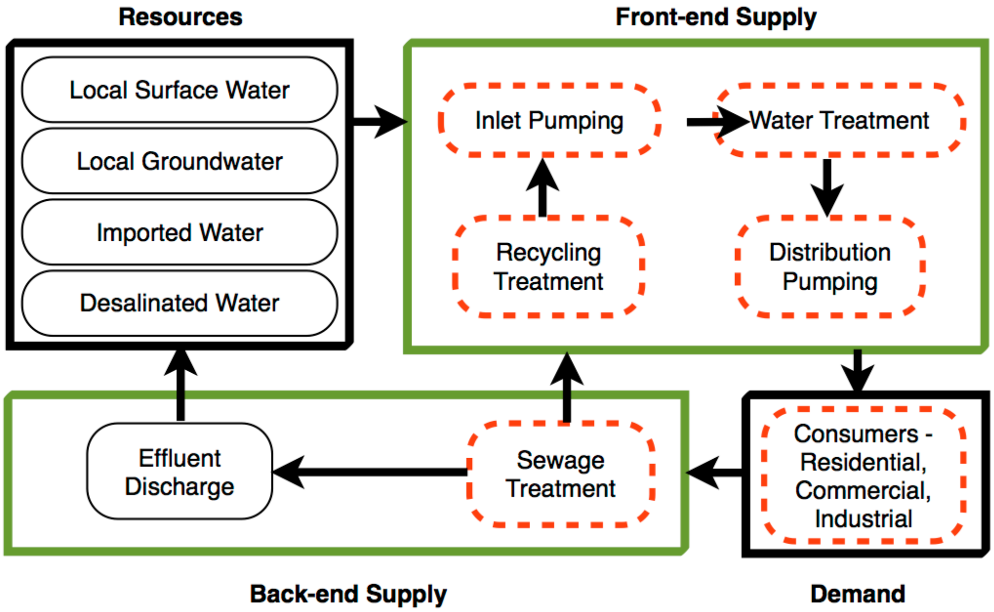

Figure 4: The Water Supply Cycle

Dashed red borders denote processes with significant energy usage, and green sections denote those included in the REWSS model.

2.2.3 Water for Energy

Water has a role in several stages of the energy supply chain. Most notably, the US uses 40% of its water withdrawals and 3% of its water consumption directly for cooling thermoelectric power plants [3]. Large withdrawals are primarily associated with open-loop or once-through cooling, which distributes waste heat over large volumes of water, evaporating only ~3% but returning the remainder to the biosphere at a higher temperature which may be detrimental [21]. The alternative, closed-loop cooling, distributes waste heat over a much smaller volume of water, but evaporates >90% of this volume, reducing the quantity available downstream [22]. The construction of additional thermoelectric power plants will likely require an available source of water that is either plentiful or capable of tolerating a temperature increase. Water is also used directly in the production of hydroelectricity from dams, where it is stored and then passed through, with minimal temperature or quantity changes. There can be considerable consumption, however, due to evaporation from the increased surface area of the reservoir [23].

Water is also a part of the transportation energy cycle, at low levels in the production of petroleum fuels and at much higher levels for irrigating biofuel crops, as well as indirectly in providing electricity for electric vehicles [24, 25]. A movement towards alternative fuels will increase indirect water use for transportation, and could increase stress on non-renewable or allocated water sources if feedstocks are grown in these areas.

In addition to stresses from expansion of current technologies, several new sources may increase the dependence of energy on water. Key among these sources are new fossil fuel extraction methods for bituminous tar sands and shale gas formations [24, 26]. With declining conventional reserves of oil and natural gas, an increasing fraction of oil and gas are being produced from unconventional sources. While the local impacts of withdrawing additional water varies by region and by origin, increasing dependence on tar sands or hydraulically fractured gas wells will lead to an increased water footprint for these fossil fuels. Large scale solar thermal power plants will also require large amounts of water for cooling, an issue amplified by their ideal placement in the high-insolation desert of the SW US [21]. While increasing electrical demand and/or a desire to move away from fossil fuel combustion may prompt the development of many solar thermal and or nuclear power plants, their water demands may place an excessive stress on the regional WEN.

2.2.4 Energy for Water

Energy is also used at several places in the water supply chain. The most widespread use of energy is for water delivery via pumping as well as for powering treatment plants. Average energy usage for water treatment and distribution across the US is 1226 kWh/MGal [27], which increases for higher levels of treatment [15]. In areas that have supplemented local water resources, such as southern California or Arizona [28, 29], additional energy is often required to pump water between watersheds or from increasingly deep aquifers. This value varies by the system, with energy-intensive systems like the State Water Project in California using 9,202 kWh/MGal [30]. Future inter-watershed projects are likely to be more energy intensive, as lower-energy ones were built first [31].

New energy sources will consume additional water and new water sources are likely to consume additional energy. Expanding local supplies has a higher energy cost, either for deeper aquifer pumping, or for wastewater reuse and/or desalination via reverse osmosis [29, 32, 33]. Additional policies on the removal of nutrients or pharmaceuticals would also increase energy consumption at wastewater treatment plants [15]. It is, however, also possible that some technologies may decrease the energy used for treatment of water by generating energy at municipal plants. Promising technologies in this area include microbial fuel cells, increased adoption of biogas collection and combustion, or the production of algae using sewage sludge [34]. These technologies can help lower plant energy consumption, but are unlikely to make treatment plants energy producers, particularly with advanced treatment requirements.

The need for more water or additional treatment to meet new regulations will likely require more energy, which may in turn require more water supplies. These two stresses on the WEN are impossible to separate, and their simultaneous analysis is critical. In addition, because some regions have plentiful renewable freshwater supplies, and others have energy supplies but very limited and/or imported water, regions will approach these interdependencies differently, particularly as non-renewable (but easily transportable) sources of energy are increasingly unpalatable due to economic or climatic concerns, necessitating the idea of the sustainable water-energy nexus.

2.3 MARCELLUS SHALE DEVELOPMENT

As conventional reservoirs of natural gas are depleted, more development is occurring in unconventional reserves, often introducing new ER&E impacts in new regions. Examples of unconventional gas reserves include shales, tight sands, and methane hydrates. Gas shales are large, thin regions of very low permeability rock which trap natural gas [35]. A map of shale gas basins in the US is shown in Figure 5. The amount of gas contained in the numerous US basins is estimated at 2500 trillion cubic feet (Tcf), with technically recoverable reserves (TRR) around 1000 Tcf and an annual US consumption of 22 Tcf [35].

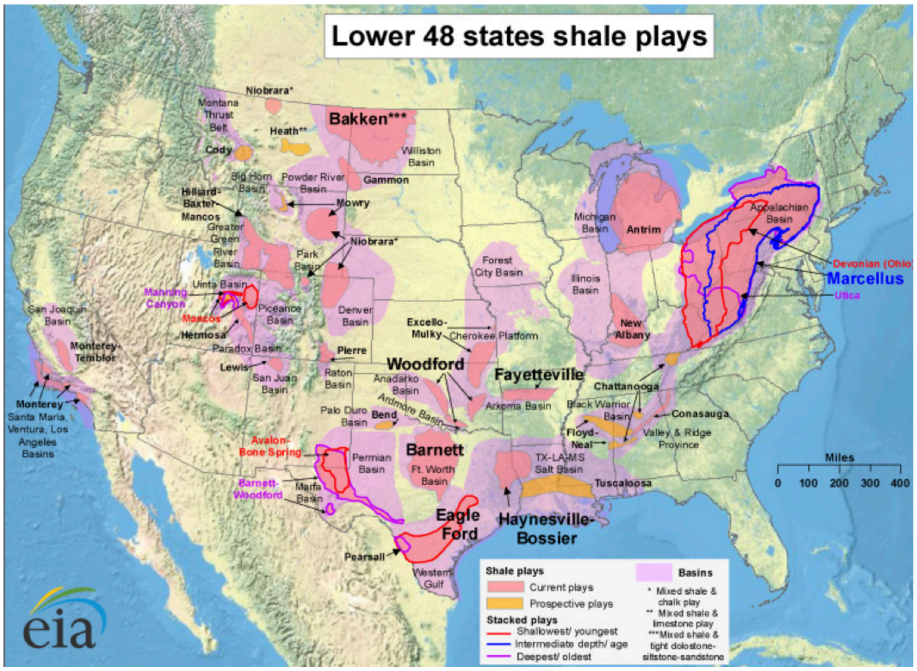

Figure 5: US Shale Plays

Includes both shale oil and shale gas fields [36]

The largest US basin is the Marcellus Shale (MS), which underlies large sections of Pennsylvania, New York, Ohio, and West Virginia. It represents 47% of US TRR for shale resources [26, 36], and production has grown by 48% per year on average from 2006-2010, making the Marcellus a key piece to consider for both the US and PA's energy future [37]. The Marcellus' potential to provide a large supply of a domestic fossil fuel with lower combustion emissions than coal is offset by concerns about the process of extracting the NG, known as hydraulic fracturing. These concerns include total water consumption during the hydraulic fracturing process [38], the toxicity in flowback water of both manmade additives and natural chemicals from shale formations [39], and methane contamination of water wells from poor gas well casing design [40], as well as larger issues such as land use (e.g. forest fragmentation) and whether shale gas will act as a transition fuel or a new dependence on non-renewable energy sources. While considerable work on process engineering has occurred [26, 41-44], peer-reviewed research on the environmental impacts has been slower to reach publication. An initial assessment of water use was completed by Veil [45], and estimates of the life-cycle global warming potential were published in a controversial study from Howarth et al. [46] and in a more comprehensive study of natural gas production pathways from Jiang et al. [47]. Osborn et al. have published a study on methane contamination of water wells in the Marcellus region [40]. These sources and others are shown in Table 1 with key findings. With the industry expanding and rapidly evolving, however, there has been little use of current operator data to append or replace decades-old estimates on methane leakage, or to examine improvements in practices over time.

Table 1: Previous Academic Shale Studies

Name	*Impacts Examined*	*Methods Used & Key Findings*
Marcellus Shale		
Howarth et al. [46]	Global Warming Potential	Estimation & Uncertainty Analysis - Using 20 year GWP, found life-cycle MS NG impacts higher than coal
Osborn et al. [40]	Methane Contamination	Water well measurements - Correlation between MS wells and contaminated water
Jiang et al. [47]	Global Warming Potential	Hybrid LCA - 100 yr GWP showed a life-cycle MS NG GWP value between conventional NG and coal
Veil [45]	Water & Wastewater Management	Surveys & Uncertainty Analysis - Total water usage is <1% of watershed availability
Other Shales		
Kemball-Cook et al. [48]	Ozone Emissions from Haynesville Shale operations	Direct measurements and scenario analysis - Ozone increase regionally could last through 2020
Alvarez [49]	Air Emissions from Barnett Shale operations	Direct measurements from operators - high total emissions relative to regional sources, significant reduction potential
Other Unconventional Oil & Gas Deposits		
Charpentier et al. [10]	Review of GHG studies for Canadian Oil Sand extraction	Review of 13 studies, finding high variation in results but life-cycle GWP generally higher than conventional petroleum

2.4 LIFE CYCLE ASSESSMENT

Although many impacts from water and energy supplies occur during the ‘use’ phase - smokestack pollution or water consumption - a significant fraction of impacts can occur upstream during fuel production or downstream in river deltas. Considering the entire life-cycle, even when only part of the impacts occur within a particular region, increases the accuracy of technology choices relative to their economic or environmental impacts. Life-cycle assessment (LCA) is a well-accepted method for quantifying impacts over the entire life cycle of a product, process, or service (PPS), from initial materials extraction (cradle) through processing and use to final disposal or recycling (grave). LCA has been codified by several organizations including the International Organization for Standardization’s (ISO) 14040 set of standards [50], and includes four distinct steps. The first step is the establishment of a functional unit and system boundaries for what stages or processes will be included in calculations. Second is the collection of data on all material and energy inputs and outputs for the processes within the system boundary, producing the life-cycle inventory of stressors (LCI). This step can often have two parts - collecting direct material, energy, and transport requirements, and then collecting more complete indirect requirements from pre-existing databases. The third step is the classification and characterization of stressors from the LCI into impact categories, using characterization factors that relate individual stressors to common reference units (e.g. CO_2 equivalents for global warming potential (GWP)). This step is frequently done using existing life-cycle impact assessment (LCIA) tools such as IMPACT 2002+ or the Tool for the Reduction and Assessment of Chemical Impacts (TRACI) [51, 52]. The final step is interpretation of results. Often these steps are iterative, with identification of high-impact materials or processes prompting additional scrutiny for those items.

While many impact categories are available through LCIA tools, for this proposal the impacts which are related to physical limits will be investigated. Impact assessment categories which can be interpreted in a cumulative manner are also beneficial. The primary LCIA categories utilized will be GWP and eutrophication, which are large-scale impacts with cumulative effects [53]. Other LCIA categories will be land occupation, water consumption, energy consumption, and economic cost [54, 55].

Many studies have used LCA to examine the impacts of energy sources, covering coal [56-59], transportation fuels [60-64], natural gas [58, 65, 66], nuclear [13, 67-70], and renewables [23, 68, 71-81]. These studies have established a general framework for the life-cycle stages of energy production, including production and processing of fuel, transportation of fuel, operations and maintenance, construction of infrastructure, and waste disposal. Some studies have examined water and wastewater treatment [82-89], and a similar supply-chain framework can be applied to water supply systems.

2.5 APPROCHES TO ENERGY AND WATER SCENARIOS

The study of planning energy and water supplies has generated a significant amount of literature, organizable into several large categories: energy and water independently, regionally-focused studies, LCA studies, and studies or methods that combine any or all of the above aspects. An overview of the studies underlying or preceding this work is shown in Table 2.

Table 2: Water and Energy Scenario Studies

Representative studies shown. Impacts include energy for water (EfW), water for energy (WfE), global warming potential (GWP).

Study Name	*Year*	*Water/Energy*	*Region*	*Impacts*	*Notes*
Marsh [90]	2008	Both	NSW, AU	EfW, WfE, GWP, Cost	Robust I-O model with NSW scenarios
Cooley [91]	2012	Energy for water supply	CA, US	EfW, GWP, Cost	Utility-targeted process model for assessing energy impacts of treatment and operational changes
Jacobson & Delucchi [92]	2010	Energy	Global	GWP, Cost	Technical assessment of eliminating non-renewables
Gallopin [93]	2000	Water	Global	None	Three qualitative scenarios for water technologies
Cohen [30]	2004	Energy for water supply	CA, US	EfW, GWP	Three scenarios for reducing energy use
Maas [94]	2010	Energy for water	Ontario	EfW	Report on current status over water life-cycle
Hoover [29]	2009	Energy for water	AZ, US	EfW, GWP	Report on current status
Utah DNR [95]	2012	Both	UT, US	EfW, WfE	State report on current status.

Much energy planning research focuses on detailed analysis of a specific technology on small timescales, as in technical assessments of optimizing wind power construction and operations[96]. These detailed but small scope studies can provide limits on feasible penetration of a technology for larger scope studies. Similarly, research around the environmental impacts of new technologies, such as unconventional oil and gas or bio-based technologies, is motivated by a need to understand these impacts for future planning [10, 97].

The development of actual scenarios – stories about possible futures – is a more limited area. The most regular scenarios for energy supply and demand are those of the EIA’s Annual Energy Outlook (AEO) [2, 98]. These scenarios provide reference cases and side cases based on established policies and sensitivity to certain small factors, with data on total demand for each source available both nationally and for multi-state geographic regions. For assessing future policies or plans on the annual or multi-year timescale, efforts have been split between identifying optimal approaches for minimizing cost or impacts and assessing impacts of possible paths given certain critical choices. Both types often focusing on a specific energy service due to the complexity of the relevant systems. Scenarios focused on particular services or technologies have included wind and nuclear power [99, 100]. The geographic scope of these studies varies from state or regional level up to global scales, with decreasing detail at larger scales. Brown, Silberglitt, and Lindenberg all examined energy scenarios for the US, and Ghanadan examined energy scenarios specifically in California [101-103]. Globally, Jacobson and Delucci focused on eliminating all fossil fuels from energy use by 2050, and some aspects of the technical feasibility of this challenge – no political feasibility was assessed [92, 104]. Energy planning has, out of necessity for a reliable system, created a connected ecosystem, but has primarily considered water during siting and construction of new power plants rather than a limit or guiding principle of planning.

Water planning has attracted less academic attention, perhaps because of the inherently regional and isolated nature of water supply and wastewater treatment networks, and the historic management by local public utilities. Acadmic work has focused on specific technologies, both in engineering better systems [34, 105, 106] and on assessing environmental impacts [83-85, 87, 107]. Other academic studies have taken a watershed approach, particularly around the impacts of climate change on key basins [18, 19, 108, 109]. Work has also examined water stress and scarcity on a regional basis, which can act as a feasibility comparison for water [110-112].

Water planning scenarios, however, have primarily been created by municipal planning bodies for their own independent system and customer base. Regional water plans can focus on specific technologies and available resources rather than optimization of a generic system [113-117]. A rare set of global water scenarios was published by Gallopin [93] focused around large-scale drivers of change at the mega-regional level, but performed no quantitative assessment of how the scenarios might play out. Water has traditionally been an isolated system with less reporting and regional differences in units (e.g. acre-feeet in the US west and million gallons in the US east) [3], and an industry that considered energy as a key but independent input.

Although energy and water have been interdependent for decades, it is only recently that they have been treated as limits on each other's development, necessitating the development of methods and tools for considering them simultaneously [1]. An excellent review of studies has been published by Marsh, as well as a history of the WEN in general [90, 118]. Many studies have been produced, though their approach has been fragmented either by geographic scope, coverage of environmental impacts, timeframe, or system boundary. Work on the WEN began with assessing connections between energy and water in specific applications [27]. Initial focus was on electricity use for water and wastewater treatment, and water use for cooling power plants [15, 22, 119]. Further efforts have dovetailed with increasing interest in tracking water requirements in the LCA community, particularly around biofuels [24, 25, 120, 121]. Similarly, reporting and reducing energy consumption for new water technologies has become more common, particularly with an increasing interest in desalination to address chronic water scarcity [34, 122, 123]. Data showing the water and energy impacts of specific technologies has been increasingly available over the last five years, although ingrained and government-driven tracking of basic metrics is still minimal [124-126].

Studies have extended the basic metrics described above – water for energy (WfE), energy for water (EfW), and environmental impacts - to examine the state of the WEN across a given service in certain regions, including Ontario, Texas, India, and many aspects of the California WEN [94, 127-129]. An excellent early example of combining WEN methods and scenario analysis is Cohen's 2004 assessment of three different regional changes in California's water supplies, usage, and the implications for energy consumption [30]. Finally, these calculation methods are being used to generate additional regional data on pieces of the WEN, including Hoover's study on electricity use for municipal water supplies in Arizona [29], or the state of Utah [95].

Two efforts in particular merit further discussion as background for this work. Wilkinson's general method for California's water supplies, published in 2000, was an early tool [28] that was later used to study Southern Californa's water basins [130]. More recently, Cooley & Wilkinson have produced a robust tool, WESim, for simulating the impacts of population, treatment options, and operational choices on energy usage and GWP [91]. This tool is aimed at water utilities in terms of data requirements and results focus, with energy as an input rather than a simultaneously changing parameter. WESim represents a process-based bottom-up model that allows users to input parameters for each facility within the system.

The most holistic WEN tool to date was published by Marsh in 2008 and examined the state of the WEN over the entire economy of New South Wales, Australia [28, 90]. Marsh's work used input-output methods [131] to model different economic, water, and energy sectors, and assessed both direct and indirect energy, water, GWP, and cost requirements. Four scenarios, built around different water supply and demand cases, were built and tested, with timepoints at 1995, 2001, and 2031. Marsh's work serves as an inspiration for holistic approaches to this subject, though it took a top-down approach that limited flexibility for examining variation in operating and construction methods and associated impacts. In addition, the path may be as important as the end destination in mitigating climate change, and an approach that takes an annual approach has additional value.

2.6 REGIONAL BACKGROUND

The research objectives of this work are to examine future energy and water supply impacts in three regions, using a newly developed tool as an approach. The three regions are the country of Brazil and the US states of Pennsylvania and Arizona. The variations between these regions in existing renewable resources and current development status – PA is relatively static, AZ is seeing a population increase, and BR is seeing population and per-capita demand for services increase – help to emphasize the regional dependence of the impacts of energy and water supplies. A brief background on each region is provided below, with details specific to the scenarios and modeling assumptions provided in Chapter 5.

2.6.1 Brazil

Brazil has 79 GW of installed hydroelectric capacity as of 2010, of 120 GW total [132, 133]. However, most high-quality dam sites, particularly in the more populous southern half of the country, have now been developed [134]. The remaining 15% of generation is primarily thermoelectric, with natural gas, coal, fission, and biomass all playing a part - with a large amount of biomass electricity used internally rather than exported onto the main power grid. Brazil currently has limited installed solar or wind generation capacity, but is planning to construct 2 GW of wind capacity in the coming years [132].

Brazil’s population increased by a factor of two between 1971 and 2008, but per-capita electricity use increased by a factor of five [135]. 96.6% of the country is connected through the National Interconnection System (Sistema Interligado Nacional, SIN), with per-capita electricity consumption driven by increasing income and available technology rather than infrastructure expansion. Brazil’s electricity has a lower life-cycle carbon intensity than that of many countries, with 208 kg/MWh vs. the US average of 748 kg/MWh [136], but the system will require expansion to meet future demands. Increases in generating capacity are expected to come from four major sources: hydropower in the Amazon River basin, natural gas, biomass, and renewables. New Amazonian dams are likely to flood larger areas per unit of capacity, have less steady water supplies, and have increased emissions from decomposition [137]. Dam sites are also likely to be further from major population centers, increasing transmission losses. While current dams have some on-going environmental impacts, much of their impacts have arguably already occurred during construction, providing advantages compared to new supplies. Natural gas (NG), the primary large-scale alternative to hydropower, has limited domestic supplies, and may require either increased pipeline capacity, or new liquified natural gas terminals. NG is also an insufficient response to the problem of climate change [138]. Expanded use of biomass in the form of sugarcane bagasse for electricity production uses a renewable fuel, but requires significant land and is available in finite quantities.

2.6.2 Pennsylvania

Pennsylvania is an excellent example of a water-rich but renewable-energy-poor region. Pennsylvania has ample water supplies with average annual precipitation of 40” [17]. Most municipal drinking water for the state comes from large rivers, with rural areas being more dependent on groundwater wells. Access to water and proximity to coal deposits has allowed thermoelectric power plants to proliferate, and the state is a net exporter of electricity. These power plants include coal, nuclear, and gas plants, all of which require significant water supplies for cooling - with low water usage for irrigation, thermoelectric power accounted for 68% of total PA water withdrawals in 2005 [3].

In terms of energy resources, Pennsylvania has significant coal resources and sits on top of the Marcellus Shale, one of the largest shale gas deposits in the world. Both of these sources are finite, and can have significant impacts during extraction. PA's solar insolation is relatively poor, and though it contains some small sections of moderate wind potential along the Allegheny plateau, its wind potential is also fairly low. The geology is cool enough that geothermal electricity is infeasible. Finally, although the state is in a temperate forest biome, its annual available biomass production is not significant enough for widespread electrical generation [139]. Pennsylvania is an excellent example of a water-rich but renewable energy poor region - although it has plenty of fossil energy resources for the near future.

2.6.3 Arizona

Arizona is in the opposite situation to Pennsylvania - water-starved but renewable-energy-rich. It is located in the Sonoran desert with annual average precipitation of 7", and obtains water from several sources, all with significant physical and legal restrictions. Much of the municipal and agricultural water comes from the Colorado River, where Arizona is a junior user during times of water stress. Phoenix also receives water from the Salt River Project, a tributary of the Colorado that is diverted at no energy cost to the city along with the Gila River. 43% of the state's water comes from groundwater sources, which have been declining over time, indicating unsustainable use and aquifer depletion [3]. Water availability is also projected to decrease with most climate change scenarios as the winter snowpack which feeds rivers decreases [18]. Arizona is pursuing both aquifer regeneration by injecting treated effluent from wastewater treatment plants as well as limited potable reuse and minimizing the expansion of irrigated agriculture. Arizona has 40 thermoelectric plants, which currently account for only 1.4% of its total water withdrawals [3, 140]. Arizona may be limited in its ability to build new thermoelectric power plants due to their water requirements. Its water supplies, particularly with a growing population, large agricultural sector, and increasing demand for the Colorado River's water, are limited at best and increasingly energy-intensive.

Arizona does, however, have one of the highest solar insolations of any state, as well as relatively high geological temperatures, enabling large scale solar as well as geothermal electricity. The state receives power from several large hydroelectric dams, though no more are likely to be built, and its wind and biomass potentials are low. It serves as an excellent example of a renewable energy-rich, water-poor area where conservation may be one of the more important paths forwards, particularly for water.

Neither Pennsylvania nor Arizona is truly limited by the WEN, but both are limited - though for opposite reasons - by the sustainable WEN. This opposition will provide a clear contrast in resources available for scenario implementation. Both states are also electricity exporters, limiting the need for inter-state adjustments to electricity generation mixes. In terms of watersheds, Arizona is almost entirely within the Colorado river basin, and its state border is either the strictly allocated river itself, or close to the edges of tributary headwaters (see Figure 6a). Pennsylvania contains the majority of the headwaters for three different river basins (see Figure 6b), and is likely to have its water resources constrained by quality regulations at specific sites rather than overall withdrawal volumes [115]. Inter-state water allocation is either already done or not likely to be necessary.

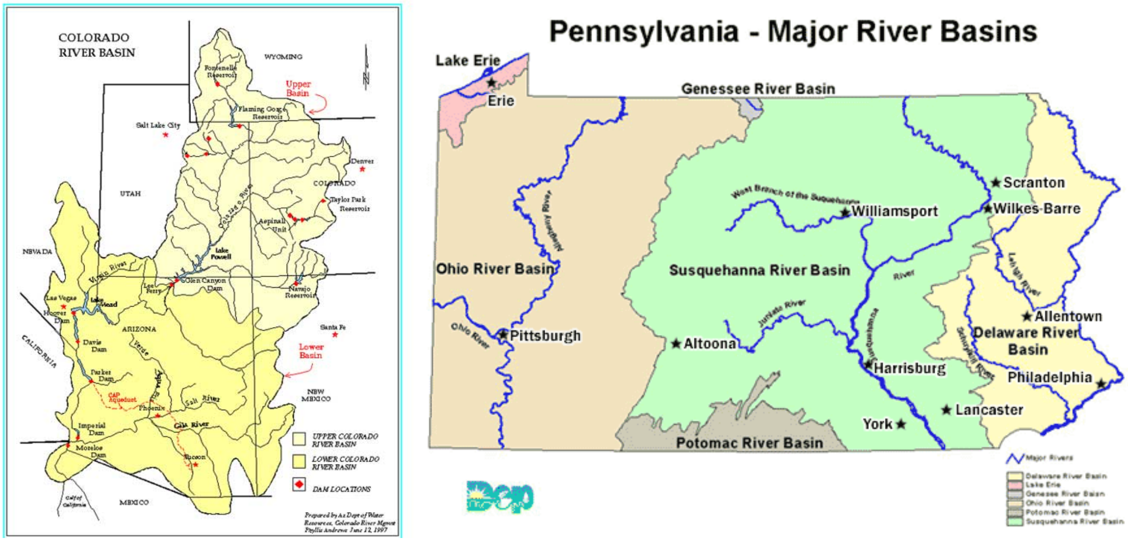

Figure 6: Case study watersheds

(a) Colorado river basin with focus on Arizona, (b) Major Pennsylvania river basins [115]

2.7 LITERATURE CONCLUSIONS

Work on the WEN to this point has mostly had a regional or source-specific focus. Studies that aim to address the WEN, either holistically or generally, require assumptions that decrease specificity. Alternatively, the majority of the work on life-cycle impacts have focused on technologies in a region-agnostic manner. This work combines these four threads – water, energy, regional scenarios, and life-cycle impacts – by synthesizing individual studies that examined technology linkages, specific regions, and those that evaluated environmental impacts or single-resource scenarios. This combination and representative literature studies are shown in

Figure 7. Sufficient data exists to permit the construction of a process-based model that can be tailored to a user-specified region and technology path. The data available, however, is constantly evolving, so such a model will necessarily require updating to maintain its usefulness. An overarching mission of this work is to show that reasonable assumptions and existing data can produce a calculation model and data structure that is amenable to non-expert use and easily updated in future years.

A key set of information that has only recently begun to appear is the environmental impacts of producing shale gas. This large reserve of energy has precipitated shifts in the US natural gas market and increased proven US NG reserves, but whether its impacts were higher or lower than conventional gas is not yet determined. While several studies have examined GWP, there is a need for research on EROI, and for more work on water consumption; water quality; and *local* air, soil and water impacts. Recent changes in drilling practices make a process-based approach to GWP a valuable contribution. In order to assess future energy supplies in the US and PA, the first section of this work performed a process LCA using operator information. This information was then used in the input data for the calculation model discussed in Chapter 4.0

This work contributes a general model for assessing future supply scenarios, but also provides region-specific information on an emerging energy source, demonstrating the additional work that may be required for assessing new regions or energy or water sources. These detailed studies provide the literature base to support more general models, and are both important for place-appropriate planning.

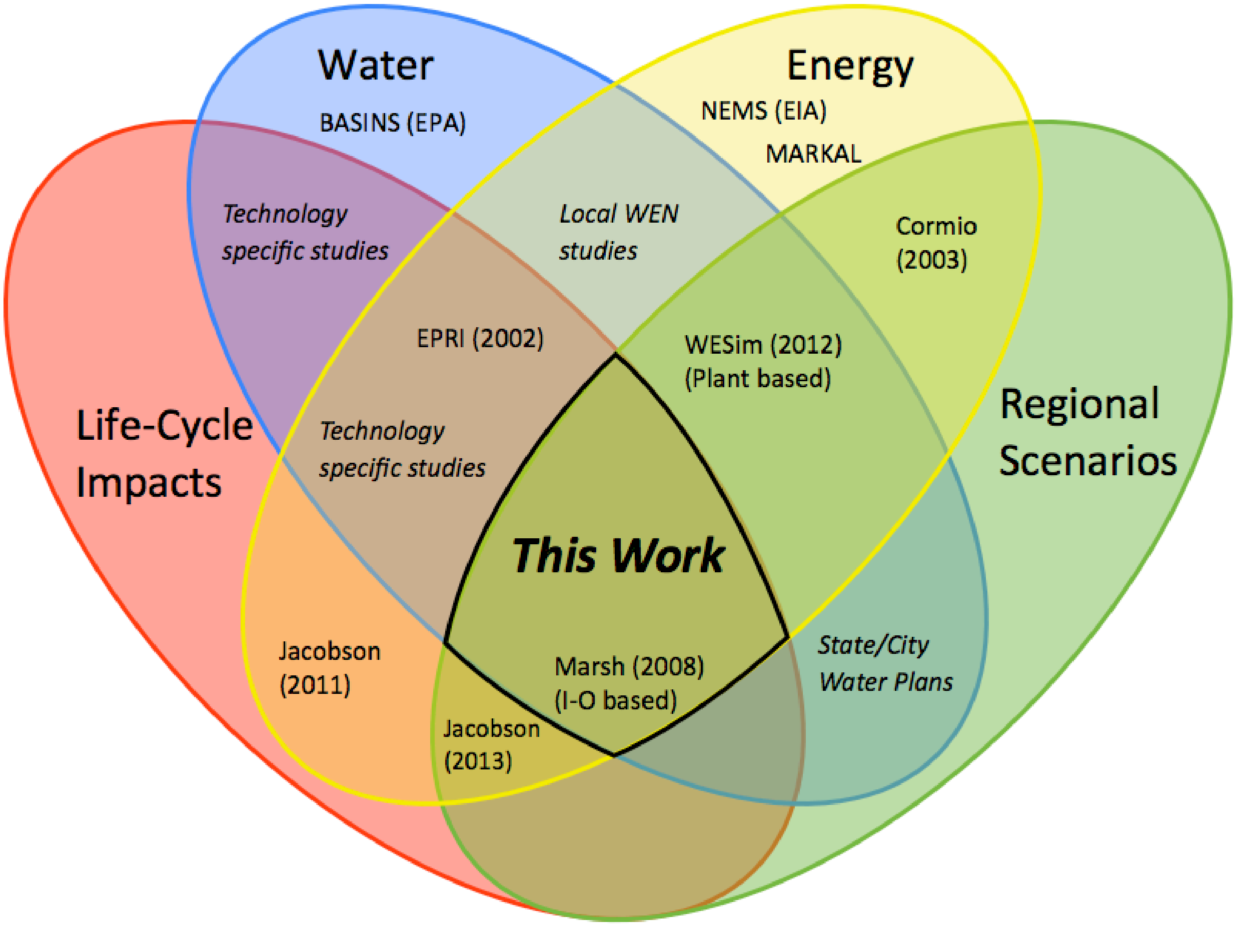

Figure 7: Intersecting themes in this work with representative literature

3.0 LIFE-CYCLE ENVIRONMENTAL IMPACTS OF NATURAL GAS FROM THE MARCELLUS SHALE

The following chapter is based on an article under review in *Environmental Science & Technology* with the citation:

Dale, A.T., Khanna, V., Vidic, R.D., Bilec, M.M., "Life-Cycle Environmental Impacts of Natural Gas from the Marcellus Shale." Evironmental Science & Technology, 2013: Under review.

The article combines the manuscript and supporting information following the second peer-review in *Environmental Science & Technology*. Additional Supporting Information submitted with the journal *Environmental Science & Technology* appears in Appendix A.

3.1 INTRODUCTION

Natural gas (NG) from shale formations represents a significant source of unconventional fossil fuels. A key large US shale formation is the Marcellus Shale (MS), which underlies New York, Pennsylvania, Ohio, & West Virginia [141]. The Marcellus' overall gas-in-place reserves have been estimated to be 1500 trillion cubic feet (Tcf), with technically recoverable reserves estimated at 84 Tcf by the United States Geological Survey (USGS) in 2011, and 141 Tcf by the Energy Information Administration's (EIA) 2012 Annual Energy Outlook (AEO) [98, 142]. In addition, the MS is located close to pipelines and major NG markets in the northeastern US, and development of it and other US shale reserves may serve as models for those in other countries.

The potential for gas shales as a new source of domestic energy has incited significant scientific, political, and public discussion, with concerns raised over both the regional and global environmental impacts of extraction [26, 143, 144]. Although significant work has been done on how to improve the technical effectiveness of shale gas extraction [42, 43], fewer studies have been published on the environmental impacts. Osborn et al. studied methane concentrations in drinking water wells, correlating an increase in methane concentration in groundwater with proximity to drilling activity [40]. Other studies have looked at ozone and general air emissions from the Haynesville and Barnett shales, respectively [48, 49], showing a significant emission increases in their respective regions. Blohm et al. have also raised the possibility that much of the MS may be unusable because of existing land use and regulation [145].

Several studies have examined greenhouse gas (GHG) emissions of conventional and unconventional gas resources. Howarth et al. [46] reported an initial estimate with life-cycle emissions similar to coal-fired electricity. Jiang et al. [47] conducted a study of the GHG emissions of MS NG extraction using a hybrid LCA of process data and the Economic Input-

Output LCA tool (EIO-LCA) and found values 11% higher than conventional NG excluding combustion but 20-50% lower than coal. Burnham et al. [97] used updated EPA estimates in conjunction with the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model [146], with life-cycle GHG emissions 8% lower than conventional NG. Stephenson et al. [147], estimated shale gas GHG emissions to be 1.8-2.4% higher than conventional gas, while Hultman et al. [148] showed 11% higher emissions. Skone et al. performed a process-based assessment that showed shale gas with 200% higher upstream emissions, but negligible differences to end uses [149]. Most recently, Weber and Clavin [150] combined five studies to show that the ranges of GHG emissions for conventional and shale gas are similar per unit of hydrocarbon production.

3.1.1 Life-Cycle Assessment

Life-cycle assessment (LCA) is a method for quantifying impacts over the entire life cycle of a product, process, or service, from initial materials extraction (cradle) through processing (gate) and use to final disposal or recycling (grave). LCA has been codified by several organizations including the International Organization for Standardization's (ISO) 14040 set of standards [50], and includes four distinct steps. The first step is the establishment of a functional unit and system boundaries for the stages or processes that will be included in calculations. Second is the collection of data on all material and energy inputs and outputs for the processes within the system boundary, producing the life-cycle inventory (LCI) of stressors. This step can often have two parts - collecting direct material, energy, and transport requirements, and then collecting direct and indirect requirements from pre-existing databases. Third is the classification and characterization of stressors from the LCI into impact categories, using characterization factors that relate individual stressors to common reference units (e.g. CO_2 equivalents for GHG emissions), followed by the interpretation of results. Often these steps are iterative, with identification of high-impact materials or processes prompting additional scrutiny for those items.

3.1.2 Well Development Process

The processes involved in bringing shale gas to market are described in detail in the Groundwater Protection Council's Modern Shale Gas Primer [35], with many processes that are similar to conventional gas wells. Shale-gas pads are large to accommodate necessary equipment for drilling and fracturing multiple wells from the same surface location, with individual well laterals drilled in different directions. There are commonly 4-8 wells per pad, though occasionally as many as 12 wells are drilled. Pads can be reclaimed once drilling and completion operations are finished, leaving the access road and a small area surrounding the wellheads and brine separation equipment as permanently occupied land.

An air rig is commonly used to drill vertically until the well is 150-300m (500-1000ft) above the shale formation. Steel casing is inserted at the surface to prevent soil from collapsing into the hole, from the surface to the base of the deepest fresh groundwater, and along the entire vertical section of the borehole. Each casing string is followed by filling the annular space with cement to isolate the well casing from the surrounding environment as a means to prevent external migration of natural gas to drinking water supplies or the surface. The transitional leg (curving from vertical to horizontal) and horizontal leg, or lateral, of a Marcellus borehole are drilled by a directional drilling rig hydraulically powered by drilling fluid. The length of a lateral varies significantly, from 450m (1500ft) to over 3050m (10,000ft) [151-153]. The lateral is also cased with steel and cemented, completing the drilling and grouting processes.

Hydraulic fracturing (HF) along the lateral is a key difference in shale gas extraction as compared to conventional gas wells. The HF process uses water mixed with sand and chemicals at high downhole pressures to fracture the shale, increasing permeability to allow gas to flow from within the fractured area to the well-bore and surface [154]. Total water usage depends on the length of the lateral and local geology but is commonly around 71,000 - 120,000 barrels per well [45]. This water can be from many sources including local streams, large rivers, or groundwater, and is transported to the well pad via trucks or pipeline networks.

When the downhole pressure is released, 10-30% of the injected water returns as flow-back [35]. In addition to additive chemicals, this flow-back water also contains high total dissolved solids (TDS) and possibly associated naturally-occurring radioactive materials (NORMs), both from the formation itself [155]. Careful management of wastewater is critical to minimizing environmental impacts, and can utilize several methods, which have shifted over time. The simplest method is to re-inject waste fluids using Class II injection wells, a common method in the Barnett Shale. However, due to unfavorable geology in much of the Marcellus shale region, there is a short supply of injection wells in the Marcellus. Through 2010, drilling fluids and flow-back water were often sent to municipal sewage treatment plants, diluted, and discharged into rivers. Concerns about the various ions (bromide) and NORMs in flow-back prompted the Pennsylvania Department of Environmental Protection (PA DEP) to halt this process during the summer of 2011 [156], and have led to a rise in both industrial treatment and the reuse of flow-back water for fracturing other Marcellus gas wells. Industrial treatment options are focused around either complete remediation using crystallization and flash evaporation, or precipitation of particulate solids to prepare water for reuse. Complete treatment of the water is energy intensive but can produce high-quality effluent and a lower quantity of injected brine. Reuse of wastewater was initially avoided because of various contaminants, but basic treatment and increasing experience have led several operators to recycle upwards of 80% of their flow-back water [157]. Ultimate disposal of residual wastewater is by injection.

In the southwestern region of the MS, the NG contains high levels of heavier hydrocarbons [158]. This 'wet gas' is processed to separate the natural gas liquids (NGL) and to regulate its MJ/m^3 content. NG is then compressed and sent to main distribution lines. From distribution pipelines, the fate of shale gas and conventional gas are identical.

3.2 METHODS

This study focused on evaluating impacts from extracting the Marcellus Shale NG using current (2011-2012) and past (2007-2010) practices from operations in Pennsylvania. Our focus was on GHG emissions, energy consumption, water consumption, and energy return on investment (EROI). Impacts were calculated for the creation of a single producing well, and per-MJ of dry natural gas. Inventory data related to pad construction were allocated equally among the number of wells per pad for the given time period.

The bulk of the data collected was self-reported from two operators in the Marcellus play ('operators'). Initial meetings and conversations with individuals from different phases of the well development process provided a detailed background on the development of a well, including specific materials, suppliers and equipment used. These discussions identified practices which are highly variable, along with practices that have evolved or improved since drilling began in the MS, and provided both specific numerical data such as casing lengths and grades of steel, and also major transportation hubs for gravel, steel, and water. A simplified data collection table on operating practices was completed by two operators who controlled 28% of both drilling and production in the MS in PA through the end of 2011. This data table is available in Appendix A. Fugitive methane emissions data were also collected from mid-stream (gas gathering and processing) companies, who process raw gas and move it to main pipelines for distribution to end users. Table 3 shows the arithmetic mean and ranges for various aspects of production based on the data from the two operators. Data collected from the operators and materials information from individual discussions were combined to create a set of direct material and energy requirements for well development.

These initial data were augmented by natural gas production and waste management information from the Pennsylvania Department of Environmental Protection (PA DEP) [157], which covered January 2007 to December 2012. Operators are required to self-report semi-annual production and waste management data for all wells under Section 212 of the PA Oil & Gas Act [159]. Issues have been raised with the self-provided nature of the information, but the database remains the only large-scale source of per-well information, and was used in aggregate to minimize errors from individual wells. The production data were used to establish average drop-off models for long-term total production. The flow-back water management data were used to determine the percentage of flow-back managed under four major methods - injection, dilution through municipal wastewater treatment, industrial treatment, and reuse for fracturing future wells, and the average distance from well to treatment facility for each method (Table 6).

Table 3: Operator responses for different aspects of Marcellus Shale Well Development

Time Period	*2007-2010*			*2011-2012*		
Process	**Mean**	**Minimum**	**Maximum**	**Mean**	**Minimum**	**Maximum**
Pad & Road Area (m^2)	22300	11150	29730	9480	8360	27900
Wells per Pad	3	1	9	6	1	12
Total Borehole Depth (m)	3220	2620	3930	3720	2740	4180
Lateral Length (m)	2900	1550	5100	4200	2500	7150
Drilling Time (Days)	25	16	34	23	13	34
Fracturing Water Consumption (bbls)	150000	N/A[1]	N/A[1]	99000	42000	130000
Gas Freeflow Time (hrs)	6	1	48	6	1	24
Initial Production Rate (m^3/day)	22000	5700	85000	28000	5700	85000

Note 1: Only a single data point was available for water consumption in older wells via the survey

Data from LCA databases were collected for each material and process used in well development - gravel, diesel consumption, water, sand, etc. Information was taken from the ecoinvent and US LCI databases for most material impacts [136, 160]. LCIA was conducted using 100-year values from the Intergovernmental Panel on Climate Change (IPCC) [53] for global warming potential (GWP) and the Cumulative Energy Demand (CED) method version 1.06 for energy consumption, which includes energy consumed at all indirect stages of production [161]. Energy consumption was collected as MJ required for each life-cycle stage, and used to calculate both per-well energy use and energy return on investment (EROI) of delivered NG using low, average, and high volume production models. Water consumption, referring to water withdrawn from a body of water without replacement, was calculated, using Equation 1:

Equation 1

$$W^c = (1 - \%Fb) \cdot (W^m - W^r) - W^{inj}$$

Where W^c is water consumed, %Fb is percent of makeup water returned as flow-back, W^m is volume of makeup water, W^r is volume of water from recycled flow-back, and W^{inj} is volume injected.

Calculation of per-well life-cycle impacts was done using Monte-Carlo (M-C) simulation. Due to limited data points and inconsistent fit for normal or lognormal distributions, triangular distributions were used for operator-provided data, with the means of the low, average, and high data points for each parameter used as the low, mode, and high points of the triangular distribution. A lognormal distribution was used for solid waste generation and normal distributions for water usage, based on data from the PA DEP and the FracFocus reporting site [154, 157]. All parameters used to model per-well impacts are shown in Table 16 with associated distribution parameters.

Each M-C trial sampled each parameter's distribution to generate a life-cycle inventory (LCI). The LCI was combined with upstream life-cycle impact assessment data for each material and process (e.g. greenhouse gas emissions and energy consumption of 1 gallon of diesel or 1 ton-mile of truck transport) to calculate the trial's greenhouse gas emissions, primary energy consumption, and water consumption. Two million trials were run for each of the two time periods, producing a sample of two million points for each impact category. The final samples were best represented by, and fit to, lognormal distributions. The mean and a 90% confidence interval of the respective distributions were used for main reported results (body of paper), and results using median impacts are reported in Table 10, Table 8, and Table 18 for comparative purposes.

Calculation of impacts on a per-MJ delivered basis combined per-well impacts with a range of production estimates as described below, with all impacts from well development allocated equally per m^3 over the well's production. Per-well and processing impacts for wet gas wells were allocated based on energy content of liquids vs. final dry gas.

EROI is normally calculated on the basis of thermal equivalence using Equation 2a - all useful energy outputs over all energy consumed, as originally defined by Hall et al. [162, 163], and specifically developed for fossil fuels by Cleveland [9]. A more recent method for calculating the EROI of fuels can be found in Murphy et al. [164]. The thermal equivalence method is useful but fails to account for differences in quality or usability, such as replacing oil with natural gas or electricity for transport. Quality-adjusted EROI methods multiply each energy source by a quality factor, λ, which can be calculated by a number of methods. This produces Equation 2b:

Equation 2

$$EROI = \frac{\sum_{k=1}^{n} E_k^o}{\sum_{k=1}^{n} E_k^c} \ (a) \qquad EROI^* = \frac{\sum_{k=1}^{n} \lambda_k E_k^o}{\sum_{k=1}^{n} \lambda_k E_k^c} \ (b)$$

Both equations from [9], with E^o representing useful energy produced and E^c representing energy consumed, for n different energy sources.

We calculated EROI using both thermal equivalence and using the price-based quality-adjustment described in Cleveland [9], which adjusts the energy from each source based on the price/MJ relative to a base energy source. Thermal EROI was calculated using Monte-Carlo simulation and the following overall equation:

Equation 3

$$EROI = \frac{EUR(1 - f_l - f_c)}{WD \cdot (1 - f_l - f_c) + EUR \cdot (1 - f_l) \cdot (f_c + f_p \cdot 3.09)}$$

Well development (WD) energy requirements were taken from the per-well Monte-Carlo distributions, which used the Cumulative Energy Demand method to calculate primary energy [161]. Estimated ultimate recovery (EUR) was calculated as described in Section 3.2.1.4, with a mean value of 72 or 108 million m^3 (mcm) over a 30 year lifetime, and a 5%/95% interval of 1.8 and 304 mcm for the '11-'12 time period. f_l refers to leakage rates, f_c to parasitic usage for compression, and f_p to processing energy. Triangular distributions were used for the three factors, and values for all parameters are given in Table 4. All three of these factors were input as percentages of delivered volume, and ranges were taken from compressor specifications, conversations with the midstream processor, and existing literature [150]. The factor for electricity was multiplied by the primary energy consumption per MJ of produced electricity for the Eastern US in the US LCI database, 3.09MJ/MJ [160]. This mix corresponds to 59% coal, 10% natural gas, 23% nuclear, 3% oil, 3% hydropower, and 2% from other sources.

Table 4: Background data for thermal EROI simulations

Case	*Distribution*	*Parameters*
Well Development (MJ)	Lognormal	Past: μ=16.95, σ=0.0939 Present: μ=16.88, σ=0.0756
EUR (MJ)	Actual wells	See Table 8 for summary statistics.
Leakage: f_l(%)	Triangular	1.1%, 1.3%, 1.5%
Compression: f_c (%)	Triangular	3.3%, 3.5%, 3.8%
Processing: f_p (%)	Triangular	1%, 1.2%,1.4%

Quality-adjusted EROI used the 2011 average cost per unit energy for major energy sources, normalized to that of coal Table 5. For each well development process, we took our best judgment as to the major energy sources - e.g. for transportation sources the energy quantity was multiplied by the quality factor of petroleum, while for steel production half the energy was multiplied by the quality of natural gas and half by the quality of electricity to model the split between virgin and recycled steel. Values for f_l and f_c were treated as NG, while f_p was treated as electricity based on current midstream activities. Combining these aspects with a similar formula as that used for the thermal EROI produced final results.

Table 5: Background data for quality-adjusted EROI

	Coal	*Diesel*	*Natural Gas*	*Electricity*
Base Unit	1 ton	1 Gallon	1 MCF	1 kWh
$/Unit	$50	$3	$4	$0.1
MJ/Unit	21,816	146	1,031	3.6
$/MJ	0.0023	0.020	0.0038	0.028
$/MJ relative to coal	1	9	2	12

3.2.1 Modeling Approaches

3.2.1.1 Pad Construction and Drilling

Information on pad area, thickness, and access road lengths was collected from the two operators. Transport hubs were used to estimate transportation distances. Total volume of pad material was calculated directly, with an assumption of common limestone gravel based on conversations. Roads were assumed to be 6.15 m (20 feet) wide. Daily fuel consumption during pad construction or drilling was multiplied by the number of days required to construct a pad or drill each well. Operators reported that both air rigs and directional drilling rig pads will burn, on average, 7570 L (2000 gallons) of diesel fuel per day. The use of natural gas as a fuel for drilling or fracturing is gaining support within the broader oil and gas industry, but is still in the experimental phase for the three Marcellus operators contacted for this study [165].

Dry cement and steel usage were based on well depth data from data tables combined with operator information on bags of cement per unit length and steel grades and weights used. All wells were assumed to have four casing strings - conductor, surface or coal casing, intermediate casing, and production casing. Based on operator reports, it was assumed that all steel arrived from Texas and Oklahoma by rail in the past, and that 20% of current steel arrived by rail from Ohio as new companies opened manufacturing facilities closer to the Marcellus.

3.2.1.2 Fracturing and Completions

Information on percent of water returning as flow-back (defined as the first 30 days), lifetime produced water, and production levels, and gas handling during breakthrough was collected to monitor completions impacts (for information on operator data, see Table 16). Because of increased public scrutiny, some well-specific information on the fracturing process is made available by a number of operators for the 2011 time period [154]. The mean values for water and sand distributions were 125,000 bbls of water and 2720 metric tons of sand for past (2007-2010) wells, with 99,000 bbls and 1810 tons for present (2011-2012) wells. Water delivery was assumed to occur either via a network of pipeline-connected impoundments or by tanker truck. No impacts were included for water pipeline delivery. Life-cycle impacts from transportation by truck were calculated on the basis of ton-miles. 70% of water was assumed to be trucked in during the 2007-2010 timeframe, and 30% was assumed to be trucked in from 2011-2012, as major operators brought pipeline networks into operation.

Information was collected on the percentage of wells that were vented, flared, or captured during completion, and average time of gas flow before the well was capped or put into production. This initial gas is the subject of many assumptions in the literature due to methane's high GWP [46, 47, 97, 166], and was calculated here based on a uniform distribution for free-flow time combined with a triangular distribution of initial flow rate which ranged from initial production levels to an order of magnitude lower.

3.2.1.3 Flow-Back Water Management

Wastewater management was modeled with four different methods: industrial treatment, re-injection, dilution through a publicly owned treatment works (POTW), and reuse for fracturing additional wells. Basic data was taken from PA DEP statewide data reports, which provide total volume of waste, treatment method, and latitude and longitude for each well and treatment facility [157]. Total barrels managed under each of the four methods were calculated for both the 2007-2010 and 2011-2012 time periods. Transportation distance for each well as calculated as the straight line distance from well to treatment plus 10% to account for roads. A volume-weighted average of per-well distances was used as the transportation distance for each method.

Each wastewater management method had impacts modeled using its major characteristics. For class II injection wells, this consisted of trucking to the disposal well and per-barrel impacts of drilling the well. For dilution through a municipal treatment plant (relevant for the 2007-2010 timeframe), trucking and water treatment through an average plant were modeled. Industrial treatment options are focused around either complete remediation using crystallization and flash evaporation, or precipitation of particulate solids to prepare water for reuse. Complete treatment of the water is energy intensive but can produce high-quality effluent and a lower quantity of injected brine. For industrial treatment, processes which used flash distillation to purify water and the energy per barrel necessary to run these processes by vaporizing water were modeled. Reuse of wastewater was initially avoided because of various contaminants, but basic treatment and increasing experience have led several operators to recycle upwards of 80% of their flow-back water [157]. Ultimate disposal of residual wastewater is by injection. For water reuse, trucking between the two wells was considered, with additional distance to a pre-treatment plant included as part of the range of transportation values. Energy for processing was included in all processes except reuse, which varies by operator and lacked available data - some operators only performed basic filtration to remove solids while others transported wastewater to a treatment facility to precipitate out additional ions before reuse. It was assumed that this energy was low compared to other methods. As with the overall per-well impacts calculation, process data from ecoinvent [136] was combined with each method's basic requirements to generate GHG emission and energy consumption figures on a per-barrel basis. Table 6 shows detailed values for all four methods.

Given unit impacts per barrel for each method and percentage of total volume managed by each method over each time period, average impacts per barrel were calculated for both time periods. The volume of flow-back generated by a given well was multiplied by this average to include the impacts of managing flow-back water.

Table 6: Marcellus Shale wastewater management data per barrel

Impact	*Industrial*	*Injection*	*Publicly-owned treatment works*	*Reuse*
Process	Flash distillation heating requirements, transportation	Transportation to well	Treatment energy, transportation	Minimal loss, transportation
Transport distance (miles)	97	78	160	9
Water Depletion (%)	25%	100%	1%	3%
GHG Emissions (kg CO2-eq)	19	7	14	1
Energy Consumption (MJ)	145	117	240	13
2008-2010 Fractions	72%	3.8%	4.4%	19%
2011-2012 Fractions	32%	11%	0.2%	57%

3.2.1.4 Production and Processing

Production estimates were calculated using per-well production reports from the PA DEP [157], and checked against operator reports of well initial production and 1st year depletion rates. Estimates from other studies are shown in Table 7 in million m^3, the default unit of production used for this study.

Table 7: Total production estimates from previous shale gas studies

Paper	*Estimate*	*Notes*
Jiang et al. (CMU Study) [11]	2.74 BCF Base case (78 mcm)	Point estimate with sensitivity analysis ranging from 0.55 BCF to 91 BCF, for well lifetimes from 5-25 years.
Burnham et al. (ANL Study) [10]	45 -150 mcm	Based on four shale gas plays, with estimates from EIA (low) and industry averages (high)
Howarth et al. [9]	85 million m3	Based on average of Haynesville shale and three tight-sands basins, no range used.
Weber & Clavin [7]	57 mcm 14 - 150 mcm	Based on six previous studies' estimates, including the others in this table.

PA DEP data is available as total production and total days of production for the whole year in 2007, 2008, and 2009, and every 6 months for 2010, 2011, and 2012. Regression was performed on each well, with production/day was as the dependent variable and center point for each time range as the independent variable (e.g. 2008 = 1.5, Jan-Jun 2010 = 3.25). A power function was fit to each well's production, and the mean value theorem was used to calculate average production/day and total production over a 30 year timeframe. Table 8 shows the median and mean mcm for the set of wells starting in the listed time period. The 'combined' row is based on the total set of wells for the time period. Production estimates for the 2011-2012 time period were based only on 2011 data due to a lack of long-term information on production for wells starting in 2012. EUR for the 2008-2010 timeframe was calculated with a mean of 72 million m^3 (mcm) and a 90% confidence interval of 0.7 and 221 mcm. For the 2011-2012 timeframe, only wells that began production in 2011 were used, producing a mean of 108 mcm and 90% confidence interval of 1.8 and 304 mcm.

As an additional analysis of the per-well data, average daily production values for the first time period each well was in production were calculated for 2010-2012 and grouped by months of production. This information is shown in Table 9, along with the number of wells in each group. Comparing wells with similar days of production over time periods can explore whether wells are more or less productive over time, but there is no clear trend in these values.

Table 8: Estimated ultimate recovery for wells starting in a given time period

Year Started	*# Wells in Sample*	*Median (50%) (mcm)*	*Mean (mcm)*
2007	40	3	11
2008	61	10	30
2009	176	13	51
2010 (Jan-Jun)	236	31	82
2010 (Jul-Dec)	255	40	87
Combined 2008-2010	728	21 (5%: 0.7; 95%: 221)	72
2011 (Jan-Dec)	843	71 (5%: 1.8; 95%: 304)	108

Table 9: Average daily production rates for wells starting in a given month of a given time period

	2010				***2011***				***2012***			
	Jan-Jun		**Jul-Dec**		**Jan-Jun**		**Jul-Dec**		**Jan-Jun**		**Jul-Dec**	
Days of Production	MCF	# wells	MCF	# wells	MCF	# wells	MCF	# wells	MCF	# wells	MCF	# wells
0-30	3411	57	3657	71	3663	88	2690	137	3177	141	6378	101
31-60	3089	57	2887	71	3630	67	4307	107	3555	107	2796	100
61-90	3076	46	3122	71	3072	74	4529	108	4295	108	6173	108
91-120	2651	40	2785	70	3321	86	2472	137	3005	144	3321	134
121-150	2494	34	2793	87	2743	133	3796	133	3272	133	2729	133
151-180	2148	36	1910	187	2381	270	2657	262	2793	277	3007	273

Impacts on a per-well basis reported the mean (50th percentile), with a 90% confidence interval from the 5th and 95th percentiles. For EUR values, the median and mean present two different options because of the relatively small number of high-performing wells. The relationship between fraction of production and fraction of wells is shown in Figure 35. The curve shows that roughly 80% of production is associated with 20% of wells. Because of this inequity, a random volume of NG is likely to have been produced at a high-performing well, with the associated lower impacts. For this reason and the knowledge of the underlying distribution, the mean value for each of the two time periods was used as the center point in calculating per-MJ impacts. The median value and associated results using it are reported in Appendix A as a comparative reference.

Four primary steps between well-pad and distribution for use were considered - leakage during initial gas processing and midstream transportation, processing to remove liquids when necessary, compression for long-distance transportation, and leakage during transmission. Based on conversations with a major midstream processor and similar studies [150, 158], mid-stream leakage was assumed to be 1.1% of total volume for past practices, and 1% for current ones due to increased usage of vapor recovery units on condensate tanks [167]. Processing to remove NGL was modeled using an electrically-powered dry gas processing module in the ecoinvent database [136]. This module shows a 1.2% energy loss relative to the energy in the output NG. Allocation of impacts for pre-processing impacts of wet gas from southwestern PA was done based on energy content, resulting in an average 75%-25% allocation for natural gas vs. liquids. The transport and delivery of NGL was not modeled in this study. Energy consumption for compression from regional gathering plants to the main transmission pipelines was assumed to be gas-powered and was modeled using operator information for actual compressors used in PA. The two relevant compressors are operated using pipeline gas, consuming an average of 3.5% of the natural gas as a parasitic load [168, 169]. No compressors were modeled for regional gathering plants.

3.2.2 Uncertainty & Sensitivity Analysis

With many different operators working in a still-developing area, there are a wide variety of operating practices, creating significant uncertainty about long-term production levels and additional fracturing operations. Calculating initial results on a per-well basis minimizes uncertainty from production levels for per-well results, but for impacts per MJ of gas delivered, production values are required. The use of Monte-Carlo methods to generate per-well impacts and the use of distributions in calculating production values allow results to be reported as percentiles rather than minima and maxima. The per-well samples for each impact category were also compared between the ’07-’10 and ’11-’12 time periods to check for statistically significant change through the use of a two-tailed t-test.

Validation of an LCA based on operator-provided data and comparison of our results to others is critical. Our LCA results were compared to published studies that focused on MS impacts, along with studies that looked at conventional NG [47, 58, 66, 97, 150]. The primary comparisons were to [47], who performed many of their calculations using a hybrid LCA method, and [97], who used the GREET model and EPA estimates of fugitive methane. Comparing our purely process-based LCA results with these two studies provided different methods and datasets for calculating similar impacts.

3.3 RESULTS & DISCUSSION

Results on a per-well, and per-MJ basis are discussed below. Per-MJ results focus on per-kWh impacts and EROI. The results indicate that the life-cycle GHG emissions of MS NG appears similar to conventional NG, with a lower EROI. Results below are based on processes and data for the Marcellus Shale, and are not necessarily applicable to other shale formations. Uncertainties are provided at a 90% confidence interval. The context of these results and broader questions about the use of shale gas are discussed in Section 3.3.4.

3.3.1 Environmental Impacts Per Well

Results on a per-well basis in three impact categories (greenhouse gas emissions, energy consumption, water consumption) are organized by stage and normalized to mean impacts for a well during the 2007-2010 timeframe, as shown in Figure 8. These results are not allocated to dry natural gas and liquids, and represent only the materials and energy required to create a single active well, regardless of long-term production. The values shown are for the mean of the final Monte-Carlo distributions, with error bars showing 90% of the distribution. These results show that a 2011-2012 well has mean impacts of $2.2 \cdot 10^6$ kg CO_2-eq, $2.2 \cdot 10^7$ MJ of primary energy, and the consumption of $8.2 \cdot 10^4$ barrels of water. Mean impacts for GHG emissions and energy decreased by 22% and 6%, respectively, while per-well water consumption showed only a 2% decrease with high per-well uncertainty. A two-sided t-test was run using 200,000 samples from the final per-well distributions to determine the statistical significance of changes in mean impacts between the ’07-’10 and ’11-’12 time periods. Changes in GHG emissions and energy consumption are statistically significant at $\alpha=.05$ with $p<.001$. Changes in water consumption are statistically significant at $\alpha=.05$ with $p=.0018$. Even with this statistical significance, the limited data underlying these tests suggests caution in applying the results to other situations.

Impacts due to diesel consumption and drilling materials - steel for casings and cement - show minimal change between time periods. Improvements in operations have not resulted in faster well drilling or more efficient drills, and casing requirements have remained constant or increased, as expected with longer laterals. Although some materials such as steel are now manufactured more locally, the decrease in transport impacts is offset by an increase in average lateral length which requires additional materials. Increased material usage increases per-well impacts, but is offset by higher total production and lower per-MJ impacts.

Table 10: Per-well impacts from Monte-Carlo simulations

	GHG Emissions (kg CO_2-eq)		*Energy Consumption (MJ)*		*Water Consumption (bbls)*	
Stage(s)	**’07-’10**	**‘11-’12**	**’07-’10**	**‘11-’12**	**’07-’10**	**‘11-’12**
Overall - Mean	2.8E+06	2.2E+06	2.3E+07	2.2E+07	8.3E+04	8.2E+04
Overall - Median	2.7E+06	2.1E+06	2.3E+07	2.1E+07	7.4E+04	7.6E+04
Overall - 5%	1.9E+06	1.7E+06	2.0E+07	1.9E+07	3.3E+04	4.0E+04
Overall - 95%	3.9E+06	2.7E+06	2.7E+07	2.4E+07	1.7E+05	1.4E+05
Pad Construction - Mean	1.0E+05	5.0E+04	1.6E+06	7.6E+05	0.0E+00	0.0E+00
Drilling - Mean	1.2E+06	1.3E+06	1.5E+07	1.7E+07	1.0E+03	1.0E+03
Completion - Mean	1.1E+06	6.6E+05	2.3E+06	2.2E+06	7.7E+04	7.6E+04
Waste Management - Mean	4.2E+05	1.8E+05	3.7E+06	1.8E+06	6.3E+03	4.7E+03

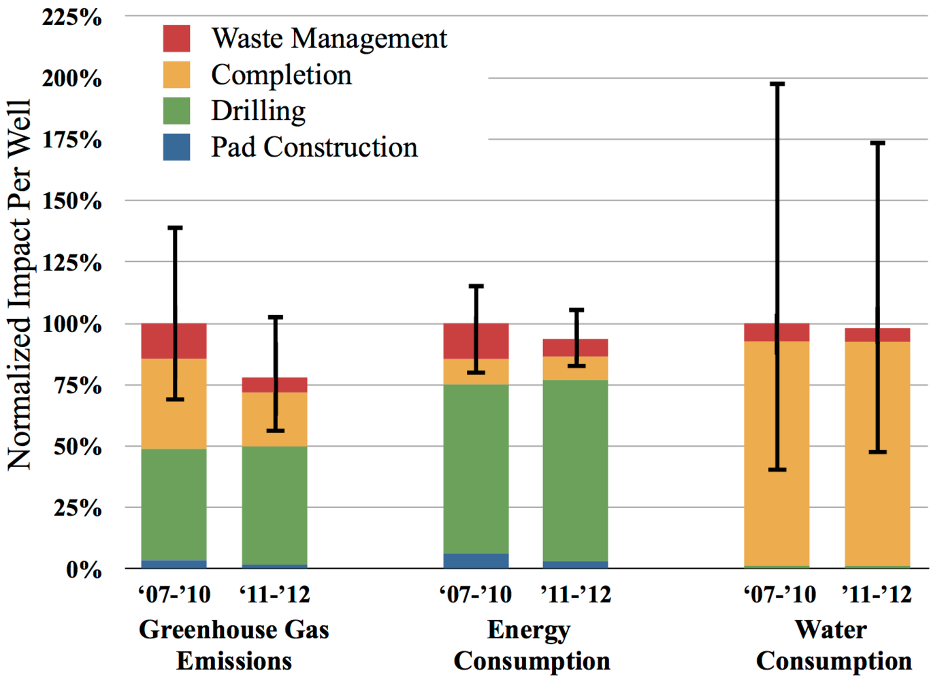

Figure 8: Phase contributions to per-well global warming potential, energy consumption, and water consumption.

Waste management includes solid waste and average impacts from wastewater practices. No allocation based on production or liquids content. Values are shown for a well with mean impacts, with error bars denoting a 90% confidence interval, and are normalized to the impacts in the 2007-2010 timeframe for each case.

These results show decreases in GHG emissions in several stages of well development. Lower impacts in the small fraction of impacts from pad construction are due to smaller pad sizes and an increase in the number of wells per pad. Lower waste management impacts come from less use of industrial treatment or municipal treatment plants and increased water reuse or injection, options with lower impacts per barrel. While gas was vented or flared for many early MS wells, practices are shifting towards capturing the gas as soon as possible, with flaring as a backup and venting as a last resort. This shift is mandated by an EPA rule which requires full compliance by 2015 [170]. These practices reduce the release of methane and its associated GWP. Energy shows similar decreases in pad construction and waste management impacts, but the changes in completion processes do not affect energy usage. In addition, with the trend towards longer laterals and resulting increased drilling time, the energy consumption and GHG emissions during drilling increased slightly between the early development and modern times.

Water usage was approximately the same on a per-well basis between the two time periods examined. Although improved fracturing processes have reduced the amount of water on a per-stage basis, longer laterals and additional fracturing stages nullify these improvements in our results. However, changes to flow-back management mean more water is reused and less is permanently disposed of in injection wells.

3.3.2 Environmental Impacts per MJ Delivered

Per-well impact data were combined with estimates of lifetime per-well production to calculate total development impacts on a per-MJ basis. While wells are similar during development (as in the impacts in Section 3.3.1), high-performing wells contribute a disproportionate percentage of total production (see Figure 35 for details). The use of mean - rather than median - production was selected in order to represent the ‘average’ volume of gas, which is more likely to be from a high-performance well. Results calculated using median estimates are available in Table 18. Additional data on impacts from gas processing, distribution, and combustion from [150] and [171] were added to include stages through delivery to customers. The per-MJ results show the relative importance of mid- and downstream processes, which contributed 96% of pre-combustion GHG emissions and 95% of pre-combustion energy consumption. Detailed values and confidence intervals can be found in Table 18. These mid- and downstream processes are similar to conventional wells, reducing any shift in impacts from unconventional well development practices, or differences between past and present time periods. In addition, increases in pad spacing, while not visible on a per-well basis, will tend to reduce the land area per unit energy, an environmental metric not investigated in detail in this work.

3.3.2.1 GWP from Electricity Generation

The per-MJ environmental impacts, allocated by energy content between dry gas and liquids where necessary, were combined with literature data on combustion emissions to calculate GHG emissions for natural gas combined cycle technologies per kWh of electricity. These results are compared for a combined cycle plant at 49% efficiency, and pulverized coal at 37% efficiency in Figure 9. The large confidence interval is a result of the wide range of production values from shale gas wells, with a spread of two orders of magnitude between the 5th and 95th percentiles.

All three shale gas studies (this work, [47, 97]) report results which are similar to each other and significantly lower than those reported by [46], a report which has been critically examined by several studies [147, 150, 172]. The primary difference in the Howarth study [46] is due to information on gas handling during completion collected in this study, which led to our assumption that a lower volume of fugitive gas was released and a much higher percentage of wells were flared or captured rather than vented. This shift in assumptions from Howarth et al. is shared by the other two studies and coincides well with operator reports, though it is clear that more study on leaked methane is critical [166].

In addition, although the primary process differences between shale gas and conventional gas occur during well development, these well development processes represent 1% of life-cycle GHG emissions (See Table 18). Efforts to reduce the environmental impacts of natural gas - conventional or unconventional - will see larger gains via efforts around efficient midstream processes, combustion, and use rather than well development practices. Other constraints or impacts, including new safety regulations, landowner preference, public health and public opinion may dictate a greater focus on drilling and completion practices.

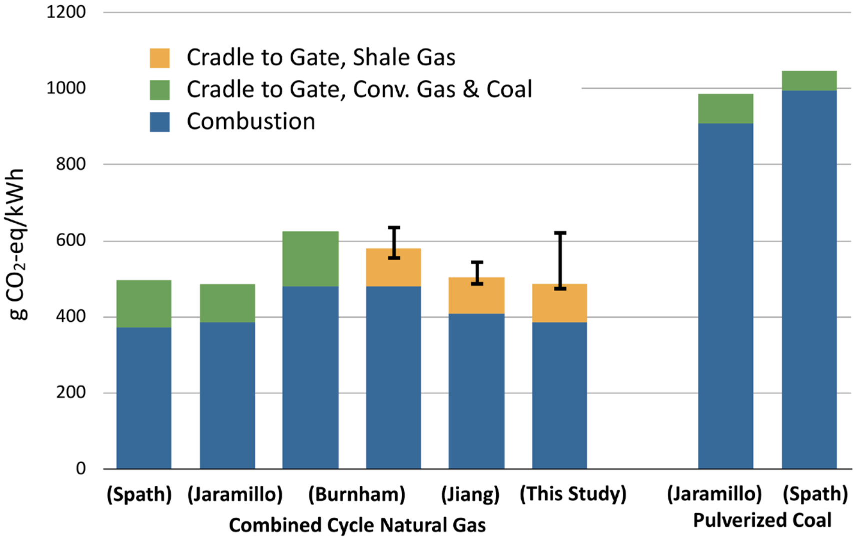

Figure 9: Per kWh comparison for GHG emissions of shale gas in a combined cycle plant (47% efficiency) relative to other conventional and shale gas studies and pulverized coal.

Error bars are: Venkatesh - high and low estimates [171], Burnham - 80% CI [97], Jiang - High and low production scenarios [47], this Study - 90% CI, with the midpoint based on mean production. Combustion information from [171] and other studies from [56, 58, 66]

3.3.2.2 Energy Consumption and EROI

The thermally-equivalent EROI was calculated for shale gas at point of delivery, considering production, processing, compression, and transmission, but not combustion. With an average 1.1% loss from leakage during midstream processing, use of 1.2% of total energy content in the form of electricity during liquids removal for wet gas, and 3.5% parasitic loss from compression, Monte-Carlo simulations of EROI showed results for the 2007-2010 time period with a mean of 10:1, a median of 12:1, and a 90% CI of 1.8:1 to 13:1, and showed the 2011-2012 time period with a mean of 12:1, a median of 12:1, and a 90% CI of 4.3:1 to 13:1. The large range is a result of high uncertainty in production rates, while the similar mean and 95th percentile are the results of the upper bound set by processing and compressive energy consumption. EROI is primarily dependent on the amount of NG used in processing and compression, with a weaker dependence on leakage, which affects delivered quantity rather than consumed energy. Processing and compression are not unique to shale gas. Calculated thermal EROI is shown against other fossil fuels in Figure 10. The thermal EROI of coal has been reported as a range from 40:1 to 80:1, higher than any modern NG or petroleum energy source [173]. A value of 12:1 places shale gas in an unfavorable position relative to conventional fossil fuels [173], but a favorable position relative to other unconventional oil and gas reserves such as the Athabascan tar sands or the Bakken shale oil formation [11]. Additional estimates of shale gas EROI would be beneficial.

Whether EROI of shale gas is rising or falling is key for planning the use of the resource. Others have noted that EROI of energy resources tends to fall over time as the easiest sources are captured first [9, 173]. Comparing the average daily production for new wells on a month-by-month basis, there is no trend in year-to-year production (Table 9). Increases in daily production might be attributed to the use of longer laterals as well as improvements in fracturing methods as operators adapt to local geological conditions. Additional long-term data is needed before trends between production and EROI can be determined.

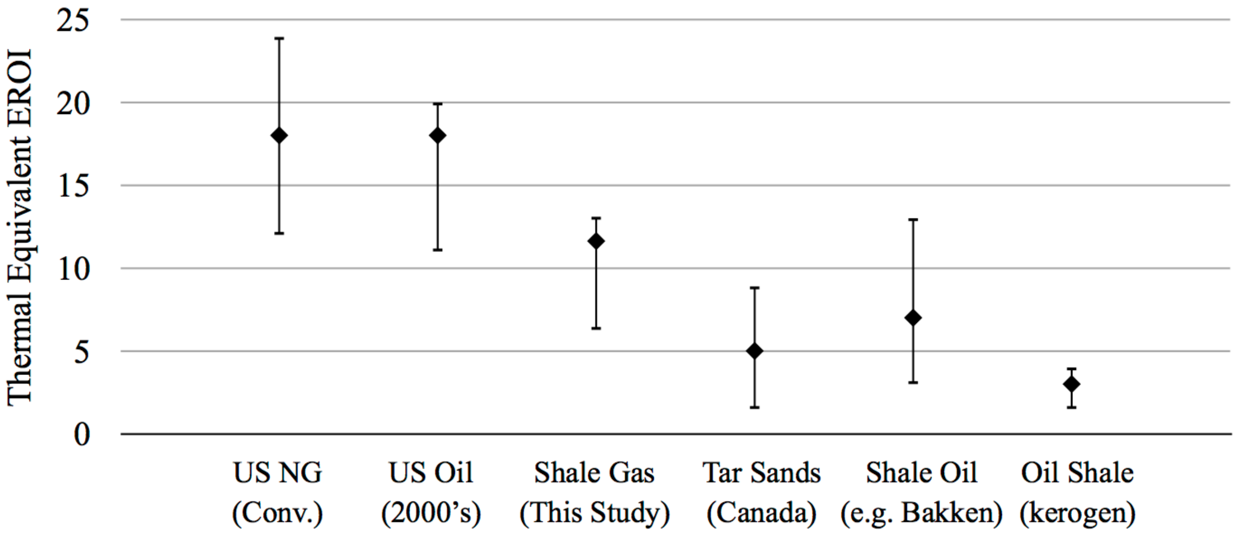

Figure 10: EROI of various hydrocarbon sources.

All sources are in thermal equivalent values. Coal is not shown for clarity as its thermal EROI has been reported at 40:1 to 80:1 [174]. The results from this study show a 90% CI and are unbalanced because of the processing energy acting as an upper bound, and the potential for very low-performing wells. These values are not directly comparable with electricity sources. US NG, US Oil from [173], Tar sands and shale oil values from [11], oil shale values from [175].

The thermally equivalent EROI does not take into account that the three main types of energy in the system - oil, NG, and electricity - are not directly substitutable. To adjust for this issue, we calculated quality-adjusted EROI using average \$/MJ prices for 2011, normalized to coal. The quality-adjusted EROI for shale gas was 4.4, with a 90% CI of 1.1-6.4. This decrease reflects the use of the more valuable/lower availability oil to obtain the less valuable natural gas, which is currently at low prices due to large production of domestic shale reserves. This price-based quality-correction approach, while illustrative, is also incomplete, as it fails to include environmental externalities from these fuels in the costs, and can fluctuate significantly with market prices. However, a quality-adjusted EROI shows that, in terms of the value placed on high-quality (i.e. concentrated and easily transported) energy forms, shale gas - and, arguably, conventional NG as well - may be less favorable than a strict thermal energy balance would indicate, particularly if more marginal areas are tapped. Calculating the EROI for electricity from the delivered NG would decrease either of these values based on the efficiency of the power plant at transforming primary energy into electricity.

3.3.3 Water Consumption

Water usage and management varies significantly by company. In terms of absolute quantity of water required per well, some operators reported decreases of up to 45% between past and present operating practices, but no notable change in water usage was visible across many operators' data. The volume used is related to both efficiency per fracturing stage, and lateral length, which is not always available. Water consumption for shale gas has been estimated by [176] at 4.4e-3 L/MJ, and was found to be one of the lowest unconventional sources in terms of water intensity.

The growing practice of reusing flow-back and produced water for fracturing will likely reduce the amount of freshwater required, but these gains may be limited. Although some larger operators are reusing 33-85% of their wastewater volume to offset freshwater requirements, this volume is limited to the 15-30% of water consumed which is returned as flow-back. In addition, if the number of wells drilled per year increases, the reused water and associated reduction in freshwater requirements is, overall, allocated among several wells, reducing the offset volume further. Operators may be recycling some of their wastewater, but because of flow-back rates and increased drilling, this practice only results in ~20% lower freshwater requirements. Even if drilling rates level off, the buildup of TDS in reused water may lead to an increase in injection volumes rather than recycled water, again limiting freshwater requirements.

Finally, in the life-cycle of natural gas, burning natural gas does produce water as a byproduct [177]. However, this water does not immediately or necessarily fall within the same watershed as it was withdrawn from for makeup water, and therefore does not offset total water consumption. With the rise of large-scale reuse of wastewater and more robust water pipeline and storage networks, high-level concerns over water consumption, at least in the relatively water-rich states which overlie the Marcellus, should be focused on excessive withdrawals from specific bodies of water or during specific times rather than overall quantity used for fracturing.

3.3.4 Broader Relevance

Relative to other unconventional sources of oil and gas, our results show that the Marcellus Shale's impacts to GHG emissions, energy consumption, and water consumption do not represent a reordering of natural gas from shale relative to impacts of other fossil fuels. This is not to say that the rise of the shale gas is a clear long-term option. Shale gas may represent a decrease in some emissions relative to coal, but it remains insufficient in meeting scientific mitigation goals for global carbon emissions [138, 178]. In addition, there are many other impacts which require consideration, including public health, ecosystem damage and environmental toxicity. These issues have not been addressed in this paper, but are essential for sound policy development. This study helps to emphasize the large uncertainties that are still present at various points of the shale gas life cycle, and the need to collect data beyond the impacts considered here.

The Marcellus as a whole represents roughly half of US shale gas reserves [35], and is geographically close to major NG markets. The per-well production rates and quality of well sites are important signals for the development of the play. While wells in the MS have shown oscillation in daily production rates rather than steady increases or decreases (see Table 9), the availability of surface rights to place well pads may be as much of a limiting factor on total extractable reserves as geological conditions [145]. The long times to prepare, drill, and complete a well, combined with low NG prices depressing drilling rates in much of the MS, may delay the appearance of decreased per-well production rates on a play-wide basis.

While individual impacts are of significant consequence to landowners and surrounding communities, and must be assessed and minimized going forward, in a wider context the Marcellus shale requires a higher-level approach to impact calculation and policy creation because its practices and development will be a model for shale gas formations worldwide. A final policy question is whether shale gas resources will be used as a transitional energy source while renewable energy sources are actively expanded, or whether their use will transform the economy from one dependent on oil and coal to one which is dependent on natural gas.

4.0 A MODEL FOR ASSESSING LIFE-CYCLE ENVIRONMENTAL IMPACTS OF FUTURE REGIONAL ENERGY & WATER SUPPLY SCENARIOS (REWSS)

4.1 MODEL OVERVIEW

To address research objective 4, and provide a method for addressing research objectives 2 & 3, a new computational model was developed, the Regional Energy & Water Supply Scenarios model, or REWSS. The REWSS model presented herein uses LCA data, current regional infrastructure and geographic conditions, and information from user-designed scenarios to calculate the total environmental impacts of supplying energy and water to a specified region. Although the model uses existing information as inputs, the underlying code and approach is novel and was developed explicitly for this work. The model is region-agnostic, but for this work modeling efforts were focused on the US sitation, with a simplified version used to assess electricity supplies in Brazil (Chapter 5.0). REWSS is written in Python for portability and future expansion, uses text files as input data, and is available at http://bit.ly/REWSS. Detailed system boundaries are described in Section 4.1, with the three-step calculation procedure described in Section 4.2. Data sources and modeling assumptions are described in Section 4.3, and the approach to uncertainty and validation are discussed in Section 4.4. The data flows for the general model are shown in Figure 11 and Figure 12.

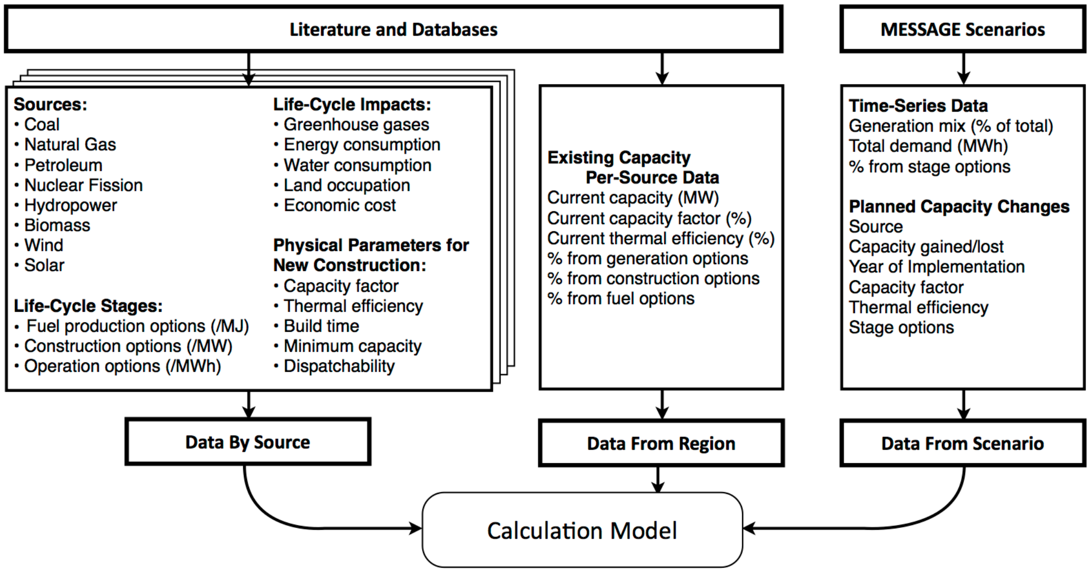

Figure 11: REWSS Model Data Flows

The data shown here is used in the calculation procedure shown in Figure 12

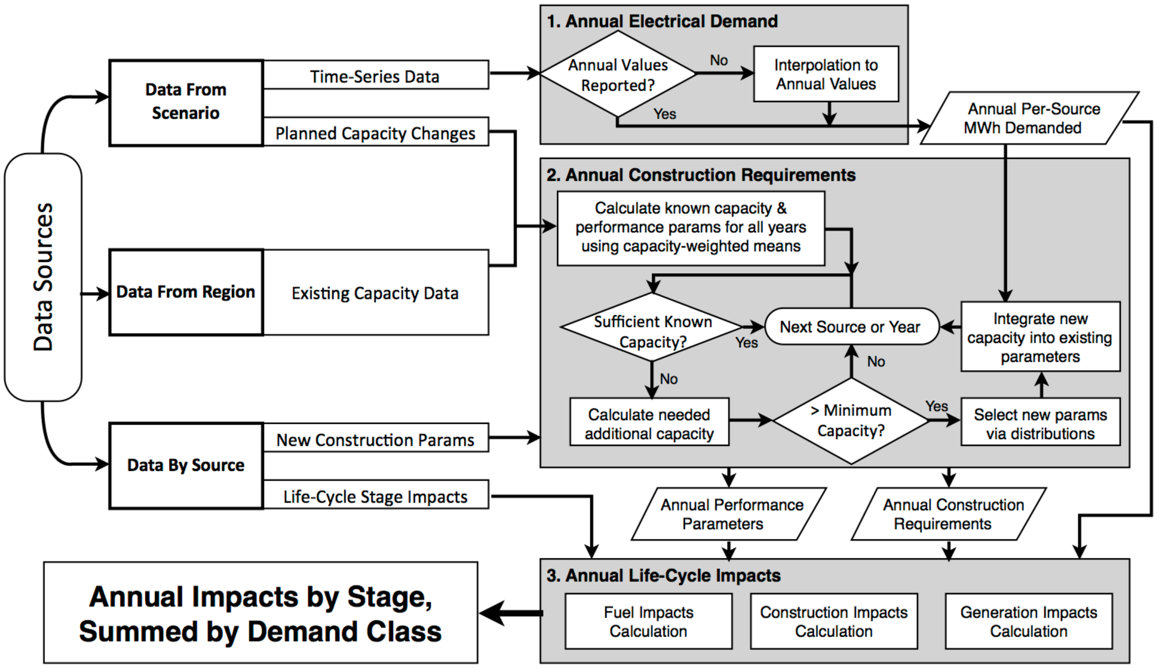

Figure 12: REWSS Calculation Model

The calculation inputs are data flows as displayed in Figure 11.

The model divides information along four dimensions: time in years, five demand classes containing 26 built-in sources of energy or water, three life-cycle stages, and five life-cycle impact categories. The five demand classes are provision of energy for electricity, heat, and transportation, provision of fresh water, and treatment of wastewater. Multiple *sources* for each class are included - e.g. coal and nuclear for electricity, ethanol for transportation, and surface and groundwater for water supplies.

A uniform framework of life-cycle *stages* is applied to all classes and sources, dividing impacts into three stages: resource production, construction of class conversion capacity, and operations. The included aspects for each class and stage are shown in Table 19. In general, resource production includes raw materials extraction (e.g. fuel or untreated water) through transport to an appropriate conversion facility, construction includes production of that facility and indirect associated impacts, and operations includes conversion to usable energy services or treated water with associated operations and maintenance (O&M) impacts. The impacts and efficiency of distribution and existing distribution networks (e.g. the electrical grid) are not included, though additional infrastructure for connecting new capacity is included in construction impacts.

Many sources have multiple *options* for one or more stages, either different methods - e.g. surface vs. underground mining, or open vs. closed loop cooling - or different regions where geographically dependent sources such as hydropower or wind energy will perform differently. Information is available on each option's environmental impacts, many of which are often similar. The annual percentage of a source or stage from each option is defined by the scenario

(Section 4.2.1). A full list of built-in supply sources, per-stage options and LCA data sources is available in Appendix B.

Table 11: Stage boundaries for REWSS model demand classes

Class	*Resource Production*	*Conversion Capacity*	*Operations*
Electricity	Fuel extraction to delivery at power plant	Power plants, no distribution	Electricity generation, Operations & Maintenance
Transportation	Fuel extraction to delivery to vehicle	Vehicles	Vehicle operations & maintenance
Heating	Fuel extraction to delivery at end user	Boiler/Furnace	Combustion, system O&M
Water Supply	Raw water pumping to treatment facility	Treatment facility, no distribution	Treatment processes, no distribution losses
Wastewater Management	None	Treatment facility	Treatment processes, including pumping from sewer mains

Impacts are calculated for five impact categories: greenhouse gases (GHGs) using a 100-year global warming potential (GWP), energy consumption, water consumption, land occupation, and monetary cost. Energy consumption considers total primary energy required, *not including the energy value of the fuel itself*. Water consumption is based on the volume of water not returned to a withdrawal source, irrespective of quality. Land occupation is defined as the physical area of land used for a given process, without consideration of changes in quality. Monetary cost is calculated in 2010 US Dollars, using the 2010 average conversion rate from foreign currency where necessary.

4.2 CALCULATION PROCEDURE

The calculation process for the model is shown in Figure 12, and consists of three large steps, outlined in grey: (1) calculation of per-source annual demand, (2) identifying necessary construction to meet required demand, and (3) combining these two requirements with LCA data to calculate annual impacts in the five impact categories. An example of input data, based on the scenarios used in this work, and the fixed parameters for each source are described in Appendices C & D. Key data inputs for the calculations are shown in Appendix B by scenario, region, and source.

4.2.1 Demand Calculation

Demand requirements are calculated separately for each class *c*, with units of MWh for electricy, MJ for transport and heat, and m^3 for water and wastewater. National-level demand is adjusted to the regional level by using Equation 4, where the absolute difference in national demand is adjusted by the fraction of a class's national demand represented by the region, F_c, with future demand changes adjusted by the expected rate of population growth P for the region relative to the nation, as determined by the US Census Bureau or state-based studies [179, 180].

Equation 4

$$D_{c,t}^{reg} = D_{c,t-1}^{reg} + \left(D_{c,t}^{nat} - D_{c,t-1}^{nat}\right) \cdot F_c^{reg} \frac{P^{reg}}{P^{nat}}$$

The fraction of a class from each of its sources is defined as the *source mix*, building on the framework of an electrical generation mix. The basic source mix is taken from the scenario data, with linear interpolation used to generate annual mixes. The source mix can be provided at either the regional level or for a larger region such as the US overall. When provided at the national level, the regional source mix is calculated using the current regional source mix multiplied by the percent change at the national level, as seen in Equation 5.

Equation 5

$$f_{s,t}^{reg} = f_{s,t-1}^{reg} \cdot \begin{cases} 1 + a \cdot p_{s,p} & a > 1 \\ 1 + a/p_{s,p} & a < 1 \end{cases} \quad for \quad a \equiv \left(\frac{f_{s,t}^{nat}}{f_{s,t-1}^{nat}} - 1 \right)$$

Here, $f_{s,i}$ is the fraction of a class from source s in year i, and $p_{s,p}$ is a preference factor that amplifies or dampens the national percent change for each source. $p_{s,p}$ represent policy-based preferences, while $p_{s,n}$ (not used in Equation 5) represents natural regional preferences for renewable sources. Natural preferences are fixed for US states, and are calculated using each state's energy potential from source relative to the national average, based on a study from NREL [181]. Policy-based preferences are set for each scenario by users.

The two preference factors are a key means of building scenarios and their use merits additional explanation. Both factors operate in an identical manner to amplify or dampen percentage changes to a particular source, with factors >1 amplifying by default and factors <1 dampening. Positive preferences for a source are assumed to attempt to minimize any reductions in use as well as amplifying increases. To account for this behavior, preferences are inverted when the source is calculated to decrease in usage ($a<1$ in Equation 4). In this case, sources with preference factors >1 will dampen reductions and sources with preference factors <1 will amplify them, accelerating shifts away from the source. This splitwise behavior allows preference factors to be used to specify a regional response to national trends. Only policy-based preferences are used when translating the overall scenario source mix to a regional level, with both policy and natural preferences used for later calculations in this section.

After calculating changes for all sources based on national pathways, known capacity changes are incorporated. These changes are part of user inputs, and an example is shown in Table 21. A more complete description of handling performance parameters and for these changes is available in Section 4.2.2, but many of these changes will change the source mix for the region and merit discussion here. The shift in source mix generated by a particular change was calculated using Equation 6, where k_n is the capacity factor, C_n the capacity, and f_n the fraction of total class demand D for the *n*th infrastructure project.

Equation 6

$$f_n = \frac{8760 \cdot k_n \cdot C_n}{D_{c,t}^{reg}}$$

Changes replace or are replaced by a specific source (i.e. a coal plant replaced by natural gas), the class default (i.e. a desalination plant replacing groundwater supplies), or a mix of all sources in the class. For mixes, both natural and policy preference factors are used to determine replacements, rather than a strictly proportional division. A final available option is to not replace the source's capacity, in which case the total demand is reduced accordingly. In all cases, the total shift in the generation mix is limited by expected changes in the overall scenario, $f_{s,i}^{reg} - f_{s,i-1}^{reg}$. As an example, if coal-fired electricity is expected to decrease by 3%, only retirements accounting for more than 3% of total generation shift the source mix, to avoid double-counting changes from known capacity changes.

This approach of tracking percentage changes allows REWSS users to examine how regions respond differently to the same national scenario or trends, as the local source mix will follow national trends but not absolute values. A final differentiating factor between regions is local policy, either to promote a specific source, limit usage of a specific source, or, as with Alternative Energy Portfolios (AEPs) or Renewable Portfolio Standards (RPSs), to set minimum usage for one or more sets of sources [182]. The REWSS model, after determining changes from known capacity changes, ensures that individual and then group requirements are met. If requirements for specific sources are unmet after planned changes, those sources are set to the appropriate floor or ceiling. If a group's total fraction of the source mix does not meet requirements, the relative proportions of its sources, again adjusted by policy and natural preference factors ($p_{s,n}$ and $p_{s,p}$), are held constant while the block's total percentage is adjusted to meet policy.

Given annual regional demand and the source mix for each class, simple multiplication was used to produce absolute per-source demand in MWh (electricity), MJ (transportation and heating), or m^3 (water and wastewater).Two further adjustments were made to absolute demand requirements to account for short and long term natural variability. For sources where generation is short term variable and not controllable (e.g. wind but not hydro), total generation was tied to installed capacity and capacity factor, with scenario requirements acting as a minimum amount. For sources whose resource supply was annually variable (e.g. surface water), annual demand was adjusted by a random percentage selected from a normal distribution with standard deviation of 3%. In all cases, insufficient or excess demand was allocated to a backup source in each class, either natural gas for energy sources or groundwater for water supplies.

4.2.2 Capacity & Construction Calculation

REWSS calculates impacts for constructing new conversion capacity, with impacts of new distribution systems excluded from the model in general, and included in specific sources when appropriate, as for wind power or imported water. Capacity factor, conversion efficiency, and percentage of capacity operating under each option for any of the three stages are tracked as performance parameters for each source. The performance parameters and capacity of existing infrastructure in the region are used as an input to the method (see Table 20 for an example), with per-source parameters for construction time, minimum capacity, and probability that new capacity would be in a given option included as pre-set defaults.

Initial calculations incorporated the effects of planned capacity changes such as retiring power plants and construction of new technologies (e.g. geothermal power, electric cars, or desalination plants). The expected performance parameters for planned changes were incorporated into the relevant source's parameters at the expected end of construction using capacity-weighted means. Retiring US power plants used performance data for the most recent year before their retirement, using the EPA's eGRID tool [183]. An example of input data for planned changes is shown in Table 20.

With existing infrastructure and planned changes included, unmet demand was calculated as the difference between required generation for a given source and year (Section 4.2.1) and expected output under the source's average capacity factor at that time. For years when known capacity was insufficient, necessary but unplanned additional capacity was calculated using

Equation 7 for each source *s* and year *t*, where *C* is capacity, *D* is demand, and *k* is the mean capacity factor for that source and year.

Equation 7

$$C_{s,t}^{new} = \begin{cases} \dfrac{D_{s,t}}{k_{s,t} \cdot 8760} - C_{s,t}^{old} & C_{s,t}^{new} > C_s^{min} \quad dispatchable \\ C_s^{min} & C_{s,t}^{new} < C_s^{min} \quad non-dispatchable \end{cases}$$

For dispatchable sources, new capacity is added only if unmet demand required more than a minimum pre-set, source-specific capacity, on the assumption that existing capacity would be run at higher capacity factors rather than constructing unrealistically small plants (e.g. 10 MW coal generators). The values for pre-set minimum capacities were based on data from the National Electrical Energy Agency (ANEEL) and Energy Information Administration, and are shown in Table 30 [184, 185]. For non-dispatchable sources such as solar or wind power, no minimum capacity is required to trigger additional construction as capacity factors are determined by natural conditions rather than artificial processes. If additional capacity iss required for a non-dispatchable source but calculated capacity does not meet the minimum amount, the minimum amount is built.

Performance parameters for unplanned capacity are selected from distributions for each addition. The sources for these distributions and overall use are discussed further in Section 4.4. The selected parameters are combined with the parameters for the source's existing capacity using capacity-weighted means. Construction impacts are included retroactively, with impacts distributed uniformly over a pre-set construction time so that the plant becomes operational in the required year. Construction time is based on government data, and additional information is in Table 30. This approach to allocating construction impacts as they occur, rather than levelizing them over the lifetime of the plant, is one advantage of this annual model. The change in results is particularly important when examining large shifts in generation mixes and the addition of large amounts of new infrastructure. The final outputs from this set of calculations are the annual per-source construction requirements and performance parameters.

4.2.3 Life-Cycle Impact Calculation

To develop REWSS, LCA data were collected for each source, stage and option, forming 530 independent points (23 sources x 3 stages x 5 impact categories + options). Estimates or distributions were developed for each point, with similar processes sharing data when necessary. During each trial, unit values (impacts per unit of demand, unit of capacity, or unit of raw resource) are selected once for each point and held constant for all years. See Section 4.4 for details on the development and use of the distributions.

Using Equation 8, unit impacts for each option *j* are combined into a single unit value for each source *s*, year *t* and stage *g*, with *I* as the vector of unit impacts and *f* as the fraction from each option of a source and stage, and in a given year. Fractions are defined using current capacity and practice, with new construction adjusting the relevant stage's options in proportion to capacity – see Section 4.2.2.

Equation 8

$$\vec{I}_{s,g,t} = \sum_{j=1}^{n} \vec{I}_{s,g,j} \cdot f_{s,g,t,j}$$

To calculate final environmental impacts, each year's 78 output vectors from Eqn. 4 (26 sources with 3 stages each) are combined with annual demand and construction requirements for each source. Operational impacts are calculated from required per-source demand. Construction impacts are calculated based on constructed capacity for each source. Upstream impacts are calculated based on per-source demand divided by efficiency. Land occupation is calculated both for annual usage for fuels, operations, and new infrastructure, as well as via a cumulative value that includes prior construction and existing infrastructure. Tracking both values allows calculation of total land occupation during a given year, as land is not consumed by occupation.

Following calculation of annual impacts for each source, impacts are aggregated into classes and adjusted to account for energy-water connections (Section 4.3.5). Results are reported annually for total impacts, impacts per-class, impacts per-stage, existing capacity, constructed capacity, performance parameters, and per-source demand. To incorporate the uncertainty of LCA data and variability of performance parameters, the entire calculation procedure is repeated many times, as specified by the user and described in Section 4.4.

4.3 DATA SOURCES AND MODELING ASSUMPTIONS

LCA data was collected from existing databases such as ecoinvent 2.1 and US LCI [136, 146, 186, 187], government agencies including the EIA, EPA, and USGS [183]; and a wide set of existing literature [54, 188-192]. The full listing of LCA data sources can be seen in Table 32 for the Brazilian version of REWSS and Table 36 for the US and released version, with median LCA impacts available in Table 22, Table 23, and Table 24 in Appendix B. Many modeling assumptions are implicit in the calculation procedure described in Section 4.2, but additional assumptions related to specific demand classes and to connecting energy and water are described below.

4.3.1 Electricity

The natural variation in thermoelectric power plant efficiency is included in the calculation of impacts from fuel production by directly increasing or decreasing fuel required. For operational impacts, a reference efficiency for each source was divided by annual efficiency to adjust combustion impacts accordingly.

Performance parameters for renewable electricity sources are often geographically dependent. Wind power potential was based on NREL estimates of regions with >20% capacity factor [193]. Solar capacity factor is based on regional insolation, with a CF of 12-18% in PA and BR and 15-21% in AZ. Additional regions would require manual input for adjustments.

Electricity exports were treated by multiplying annual electricity-related impacts by the share of generation consumed within the region. Impacts of imported electricity are not included, as demand for electricity is based on in-state consumption, and all three regions used as case studies for this work are net electricity exporters or functionally isolated. Future work on net electricity importers will include imports from surrounding states or expand capacity and regional source mix to use a subset of a larger regional grid. While regional electricity grids for PA and AZ do not correspond well to state boundaries, the use of a subset of capacity, on the assumption that the region as a whole will follow similar trends, provides a way to maintain the state focus for data availability while better matching actual electrical grid conditions. Sensitivity analysis using the RFC and WECC grids was performed for PA and AZ, respectively, and is discussed in Sections 6.2.2.5 and 6.3.2.5.

4.3.2 Transport and Heating

Demand for transportation and heat services is calculated based on primary energy consumption rather than end services because of data availability and the diversity of infrastructure options. Measures of ‘capacity’ and efficiency are therefore non-conventional - efficiency captures produced but leaked or unburned fuel. A theoretical ‘average vehicle’ was created by dividing vehicle miles traveled (VMT) in 2010 by associated energy consumption [8, 194], with a resulting energy intensity of 4.7 MJ/km, and a consumption of 8.1 MJ/hr (2.25 kW) for an annual distance of 15km. The capacity factor of future additions throughout transportation sources used 4.7 MJ/hr as a reference value with capacity factor of 1, assuming that that driving habits on a vehicle basis remain the same on average. Decreases in total VMT are captured by lowering demand, while changes in miles per vehicle would be reflected by increasing the capacity factor of the entire fleet. Capturing fuel economy in capacity factor produces the appropriate behavior for building additional capacity based on demand - for the same demand, building lower CF infrastructure (efficient cars) requires more infrastructure, while a decrease in both demand and capacity factor may require no new cars, representing efficiency gains without additional services. A similar approach is used for heat, using 80% fuel utilization efficiency as a reference value for various boilers or chillers across sources.

REWSS approaches high-efficiency vehicles as an efficient way of providing a service rather than a switch in energy sources. Switches between energy supply sources such as oil, biofuels, and electricity require shifts in infrastructure and environmental impacts that are best met with a life-cycle assessment approach. Infrastructure additions and capacity is important for tracking impacts of switching between these technologies - BEVs to replace ICEVs, for example.

4.3.3 Water

Water crosses borders, but impacts related to water often are either cumulative or location-specific. REWSS uses water withdrawals as a demand class, but water consumption as a more definitive environmental impact. Water quality metrics are critical for sustainability but would require a different approach to regionalization that is has not yet been developed – see Future Work in Section 7.3. Water consumption data was mostly taken from technology-specific studies [119, 176] rather than life-cycle databases, to avoid including primary water flows that were withdrawn but not consumed. Where no other option existed – primarily for construction impacts – the ReCiPe LCIA method [187] was used to determine total water usage, based on withdrawals. These flows made up <5% of flows in all scenarios examined in this work, and <2.5% in all but one scenario, making any misallocated withdrawals a negligible issue.

Water sources are based on provision of raw water from surface sources either within or outside the watershed, groundwater, or deionization of degraded sources such as brackish water or municipal wastewater. Various levels of treatment, with increasing energy demand to remove more pollutants, are included as options for infrastructure. Energy consumption is taken from studies by EPRI, while cost information is taken from existing literature or modeling methods [15, 195]. For non-potable uses such as irrigation or cooling water, minimal treatment impacts are included to represent basic filtration or conditioning.

4.3.4 Wastewater

Estimates of wastewater treatment demand and capacity are taken from the EPA's Clean Watershed Needs Survey (CWNS), which contains real and design flow rates for all permitted infrastructure in the US [196]. The CWNS also provides information on treatment processes, which was used to generate a source mix for wastewater. REWSS does not consider individual systems that do not treat wastewater for release into an existing waterway. Negligible impacts for moving wastewater to a treatment facility are assumed, with pumping including as part of facility operations, and construction of distribution infrastructure considered outside the scope of this work.

4.3.5 Energy & Water Connections

Energy and water are treated separately for the majority of calculations, with connections primarily calculated based on impacts. Several sources have the potential to shift energy and water requirements beyond demand predictions from the overall scenario, and these are included as follows. For sources which use electricity to provide transportation or heating, capacity and demand is tracked within the final class. After impacts are calculated in Section 4.2.3, the energy consumption for operations (e.g. electric vehicles) is used to allocate impacts from electricity generation to transportation.

The primary energy use for water and wastewater provision is electricity, and calculating impacts for water-related classes using LCA values directly would double count electricity-related impacts for the region. To avoid this issue, impacts from electricity are shifted to water treatment after annual impact calculation, with the assumption that 80% of energy consumption was in the form of electricity. This approach accounts for shifts in electricity impacts from a shifting generation mix, as well as calculating an accurate overall impact for supplying energy and water to the region as a whole. An identical procedure was followed for wastewater with the same assumption of 80% energy used being in the form of electricity.

Changes in water and energy sources may increase energy and water consumption in ways unaccounted for in the source mix. This additional consumption creates additional impacts for each demand class. To calculate additional impacts, the energy intensity of water classes or water intensity of energy classes for each year relative to the start of the scenario is used to calculate additional demand for that class. This additional demand is multiplied by impact intensity for that year, effectively scaling current infrastructure. This procedure is captured for the water intensity of electricity and the energy intensity of water treatment in Equation 9 and Equation 10, respectively.

Equation 9

$$\Delta I_{t,Wat} = \frac{I_{t,Wat}}{D_{t,Wat}} \cdot \left(I_{t,Elec}^{Wat} - I_{0,Elec}^{Wat}\right) \cdot \frac{D_{t,Elec}}{D_{0,Elec}}$$

Equation 10

$$\Delta I_{t,Elec} = \frac{I_{t,Elec}}{D_{t,Elec}} \cdot 0.8 \cdot \left(I_{t,Wat}^{En} - I_{0,Wat}^{En}\right) \cdot \frac{D_{t,Wat}}{D_{0,Wat}}$$

To report connections between water and energy services as part of results – after adjusting impacts – ratios are defined between class impacts and class demands as shown in Equations 10-13, which define the % of electricity used for water (LfW), % of energy used for water (EfW), the % of water used for electricity (WfL), and the % of water used for total energy (WfE). These terms do not encompass the quality or sustainability of their components, but serve as simple metrics for the connectedness of energy and water supplies in a given region. The focus on electricity is a result of its prevalence in existing regional WEN studies, as either an input or an output; expanding to include the more complete water and energy supply chain is less common but potentially equally relevant for future planning. These metrics are calculated for each year, and reported for 2010, 2035, and an average for the time period.

Equation 11

$$LfW = \frac{I_{t,Wat}^{En} + I_{t,WW}^{En}}{D_{t,Elec}}$$

Equation 12

$$EfW = \frac{I_{t,Wat}^{En} + I_{t,WW}^{En}}{D_{t,Elec} + D_{t,Trans} + D_{t,Heat}}$$

Equation 13

$$WfL = \frac{I_{t,Elec}^{Wat}}{D_{t,Wat} + D_{t,WW}}$$

Equation 14

$$WfE = \frac{I_{t,Elec}^{Wat} + I_{t,Trans}^{Wat} + I_{t,Heat}^{Wat}}{D_{t,Wat} + D_{t,WW}}$$

4.4 UNCERTAINTY, VARIABILITY, AND VALIDATION

4.4.1 Uncertainty & Monte-Carlo Approaches

One of the core features of REWSS is the built-in handling of uncertainty in input data through Monte-Carlo (M-C) approaches. Two types of uncertainty are targeted. The first is potential error, in that life-cycle impacts are rarely precisely known. The second is variability between both artificial and natural systems. Capacity in all five demand classes can be built with varying performance standards, including higher efficiency, an intention of operating at a higher capacity factor, or overbuilding treatment capacity to plan for the future. Alternatively, some natural systems vary on an annual basis, such as the amount of surface water available for use.

Both potential error and variability are included by selecting values from ranges at various points during calculations. Potential error is captured by using a range of values for each source, stage, and impact category over the course of many trials, with a single set of values used for all years of the same trial. Variability is included by selecting a new set of performance parameters for each new capacity addition, and applying a normally-distributed random multiplier to naturally-varying sources for each year. Excess or insufficient supply is provided by the default class source.

The ranges for any of the above parameters can be one of four distributions: uniform, triangular, normal, or lognormal, with the ability to add additional distributions as necessary. All distributions are stored in code, and intended for modification by advanced users that are adapting REWSS' LCA data for new regions, or adding new technologies. For this work, LCA data taken from literature sources used primarily triangular distributions, with uniform distributions when no center point was evident. Both of these distributions are less specific about the nature of the true population, but common approaches for data-scarce situations. For values taken from LCA databases such as ecoinvent, more robust distribution data were available and normal or lognormal values were obtained by running M-C simulations on database processes.

For each trial, a single set of LCA impacts were chosen for each source, stage, and any options. An overall impact by stage was generated as a linear combination of the options, based on annually tracked changes. New capacity had performance parameters determined from triangular distributions for capacity factor and thermal efficiency as often as it was added. The impacts of any single trial are thus randomized and not necessarily representative, and are instead summed across all stages and sources to produce a ($5 \times t$) array with total impacts for each year. These total annual impacts for each of the five impact categories are stored for each trial. After N trials are calculated, the 5th, 50th, and 95th percentiles for each year and impact are reported. This approach reports the median rather than the mean, eliminating the effect of very high-impact trials skewing results upwards, with the side effect of minimizing worst-case scenarios.

To identify an appropriate number of trials, batches of 10 simulations were run with an increasing number of trials. The standard deviation of the cumulative impacts at the 50th percentile was calculated for each batch. The use of 6500 trials was found to have a standard deviation of <0.1% for any impact category. This small variation in central results was taken to be sufficient, particularly in light of the relatively high uncertainty in impact categories such as water consumption and land occupation. 6500 trials were used for all results shown in Chapters 5.0 and 6.0 .

4.4.2 Model Validation using Past Data

In addition to determining the number of trials necessary to identify a consistent central result, the overall model required validation against known impacts to verify calculation methods and LCA data usage. The model was run using information from 1990-2010 for the two case study states. Energy information was taken from national-level EIA records, with the combined non-electrical residential, commercial, and industrial energy demand used as the demand for heat as a demand class. Electrical generating capacity as of 1990 was used as a starting point, with minimal additional capacity forced in as a test of the model's procedures for determining new capacity needs. Water demand and freshwater sourcing was taken from the 1990, 1995, 2000, and 2005 USGS reports on water usage in the United States. Wastewater information was interpolated from the 1996, 2000, and 2008 CWNS performed by the EPA [196], which provided annual wastewater flow treated, design capacity of existing infrastructure, and compatible ranking of plant treatment technologies.

After running the model for both PA and AZ, the results for energy technologies were compared to EIA and EPA records for GHG. Results are visible in Figure 13 and Figure 14. The results show similar pathways between model results and actual records in most demand classes across the two states. Where variation in GHG emissions exists – such as state impacts decreasing in the model but increasing in actual records – the cause can generally be traced to rapid changes at the state level independent of national trends.

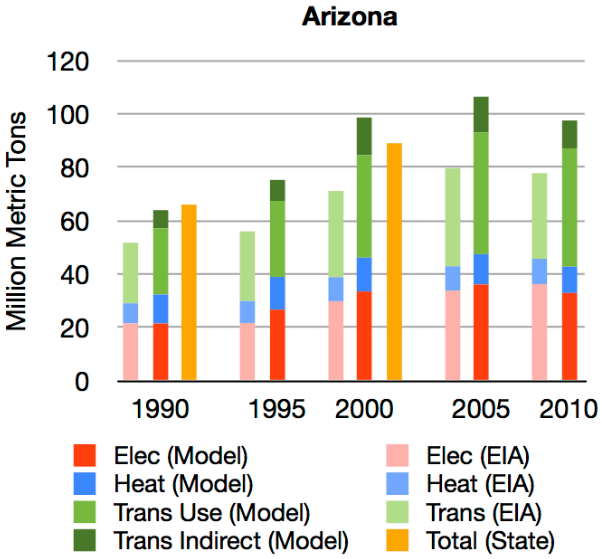

Figure 13: Comparison of model and historical GHG emissions for Arizona (1990-2010)

EIA values consider only combustion of fossil fuels. The total values from the PSU study are for the life-cycle of all energy sources.

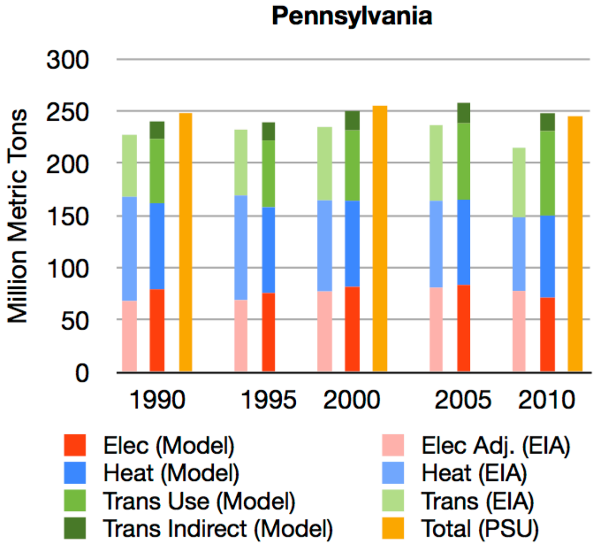

Figure 14: Comparison of model and historical GHG emissions for Pennsylvania (1990-2010)

EIA values consider only combustion of fossil fuels. The total values from the PSU study are for the life-cycle of all energy sources.

Absolute GHG values are generally higher for the model results than the recorded values. For some measures, such as EIA GHG emissions, there is a different boundary condition in that the EIA only calculates combustion emissions from fossil fuels, which account for 90%+ of total emissions. Few records separate construction from ongoing impacts, adding different bulges to the model results. Finally, the volatility in costs of energy supplies, particularly in the 2000's, is not easily included in the model, leading to a disparity near the end of the time period between model and records. Expanding capabilities for changing costs is part of future work with the model, discussed in Section 7.3.

One key approach in building this model was to capture the essence of how energy and water systems operate and calculate key parameters, while avoiding some operational details such as electricity dispatching or variations in water treatment trains. These details introduce uncertainty in several forms, which is robustly included via M-C methods capable of incorporating many different distribution types. The inclusion of uncertainty as a back-end process allows results to also report a confidnece interval while allowing users to focus on scenario construction rather than data robustness. Valdiating the model against past records shows reasonable agreement, taken to be sufficient for discussing relative paths going forward.

5.0 APPLYING THE REWSS MODEL: ELECTRICITY IN BRAZIL

5.1 INTRODUCTION

Development in Brazil has been paired with an increase in energy and electricity use for both per-capita and overall demand [197]. While Brazil currently generates 70% of its electricity from hydropower, increasing demand and the diminishing quality of dam sites will likely increase the generation from other sources. All electricity generation options, including additional hydropower, contribute to environmental impacts such as climate change, land transformation, and water stress/quality. While existing models and studies have assessed effects of low-carbon scenarios, they often omit certain impacts (e.g. emissions from hydroelectric reservoirs) or consider a limited set of impacts or life-cycle stages (e.g. ignoring construction). With the expectation of significant additional generating capacity and need to consider limited resources such as water and land, a broader approach is required for effective energy or environmental policy. This chapter focuses on applying an adapted version of the REWSS model to assess environmental impacts of future electricity generation scenarios in Brazil. REWSS is designed to provide quantitative insight into the dominant sources of various impacts, as well as the implications of proposed policies.

5.1.1 The Brazilian Electricity Grid

Brazil has 84 GW of installed hydroelectric capacity as of 2012, and 130 GW total installed electrical generating capacity [132, 133]. However, most high-quality dam sites, particularly in the more populous southern half of the country, have now been developed [134]. Thermal power plants, mainly from natural gas, coal, nuclear fission, and biomass, represent 28% of the Brazilian power grid - with a large amount of biomass electricity used internally rather than exported onto the main power grid. The remaining 6% of generation imported, primarily from Paraguay. Brazil currently has limited installed solar or wind generation capacity, but is planning to construct 3 GW of wind capacity in the coming years [132].

Brazil's population increased by a factor of two between 1971 and 2008, but per-capita electricity use increased by a factor of five [135]. 96.6% of the country is connected through the National Interconnection System (SIN), with per-capita electricity consumption driven by increasing income and available technology rather than infrastructure expansion. Brazil's electricity has a lower carbon intensity than that of many countries, with 208 kg CO_2/MWh vs. the US average of 748 kg CO_2/MWh [136], but the system will require expansion to meet future demands. Increases in generating capacity are expected to come from four major sources: hydropower in the Amazon river basin, natural gas, biomass, and renewables. New Amazonian dams may flood large forest areas, have less steady water supplies, and have increased emissions from decomposition [198]. Dam sites are also likely to be further from major population centers, increasing transmission losses. While current dams have ongoing environmental impacts, much of their impacts have already occurred during construction, providing time-dependent advantages compared to new supplies. Natural gas (NG), one of the primary large-scale alternatives to hydropower, currently has limited domestic supplies. New supply prospects include associated production from the pre-salt offshore oilfields, increased pipeline capacity, or increased liquified natural gas (LNG) imports. NG is also an insufficient response to the problem of climate change [138]. Expanded use of biomass in the form of sugarcane bagasse for electricity production uses a renewable fuel, but requires significant land and is available at a finite annual rate. Questions of which sources to pursue or encourage require new tools to integrate multiple sets of data, particularly when considering future environmental impacts, and REWSS offers one strong approach to the matter.

5.2 REGIONAL MODELING APPROACH

Brazil's electricity is generated using similar methods to US and european technology in many cases, an assumption aided by international engineering firms and shared technical knowledge. Two sources required particular adjustment: hydropower and biomass. These have been noted by Coelho as harboring the most differences, particularly because of the differences in climate between the two regions [199].

5.2.1 Hydropower

Land Use. Brazilian hydroelectric dams were generally constructed primarily for electricity generation, such that allocation for co-products such as irrigation, navigation, and flood control is less appropriate than in other countries. We assigned all impacts from reservoir emissions and dam construction to electricity, consistent with previous studies [110]. To account for the wide variation in land use, we separated dams into temperate and tropical categories. After collecting information on reservoir size for 31 dams based on Electrobras and ANEEL information, we calculated distributions in km^2/MW for both regions [132, 200]. For each new dam, an impact factor was selected from the appropriate distribution based on the dam's probable location (increasingly weighted towards tropical regions over time), and included in the regional unit impact factor for each year based on capacity-weighted means. This approach separates the natural variability in reservoir size from simple uncertainty in LCA impact factors. Water consumption due to reservoir evaporation was based on Brazilian results from Pfister et al., with an assumption of 10% uncertainty [110].

Reservoir Emissions. The impacts of hydroelectric dam operation for maintenance were included via data from ecoinvent [136]. While dams themselves do not release combustion emissions, the reservoir can be responsible for significant GHG emissions, particularly when flooded biomass decomposes anaerobically. The studies that have examined CO_2 and CH_4 emissions from Brazilian reservoirs have identified high emissions in several tropical cases, and agree that these emissions are significant and currently excluded from most studies [137, 201-204]. Measurements to date have only managed to assess gross emissions, and information about net emissions for the reservoir area before and after flooding are highly uncertain. While rivers can be net sources of GHGs, surrounding forest land are generally considered to be net carbon sinks [205]. In tropical regions, the lower land gradient and seasonal rainfall can expose and flood large amounts of land, producing annual decomposition in addition to decomposition of initially flooded material [206]. These impacts, combined with the eliminated primary productivity of the missing forest, suggest that some portion of gross emissions are likely net emissions, though there are few estimates of the actual relationship.

Impact factors for reservoir GHGs were calculated in the same manner as with land use for infrastructure, with starting values of 29 kg CO_2-eq/MWh and 543 kg CO_2-eq/MWh for temperate and tropical dams, respectively, and distributions for GHGs of future dams based on existing research cited above. This provides an estimate of gross reservoir emissions. Assuming that net emissions are some fraction of gross emissions but still positive, we calculated and reported reservoir emissions separately from other GHGs impacts for three cases: a low case where net emissions were 10% of gross emissions, a median case where they represented 50%, and a high case where they represent 90% of gross emissions.

5.2.2 Biomass

Over 95% of biomass electricity in Brazil is from waste material burned by independent producers as a byproduct, primarily sugar cane bagasse with some black liquor from paper mills [207]. Originally producing heat or power solely for internal process consumption, many plants are converting their generators to produce additional electricity to sell to the grid [208]. We counted only exported electricity, not that used on site, as part of the scenario's impacts. For this exported power, we used economic allocation for impacts based on the value of sugar and ethanol relative to electricity, and the relative production of each from a ton of sugar cane. Allocation for GWP and energy consumption was based on Seabra et al. [209], while water consumption was based on [120]. Assumptions about performance were similar to those for NG, but we assumed that capacity factors will not rise significantly, as biomass is a seasonal generation technology.

5.3 SCENARIO DESCRIPTION

The electricity scenarios used in this work were based on the coupling of the IAEA's MAED and MESSAGE models. The two models combine top-down assumptions, such as economic and population growth, bottom-up disaggregated sectoral information, and constraints related to energy resource availability to produce energy demand and optimal energy supply scenarios. The demand component (MAED) provides detailed sectoral energy demand projections while a linear programming energy supply optimization model (MESSAGE) provides the least-cost energy and electricity supply mix scenario. For further information, see [210]. The MAED-MESSAGE models have been applied in several different energy studies [210-214]. The models were used in this study to create future scenarios for the electricity sector in Brazil. The premises for this work, as well as the central structure of the Brazilian implementation of MESSAGE, are derived from Borba [215].

Five scenarios were developed using MESSAGE: one reference case and four alternative scenarios or side cases, based on more or less intensive implementations of biomass and solar technology. The reference case has been used in previous work in a different context; the side cases were developed for this study. The reference case is an attempt to simulate a business as usual (BAU) trajectory for the Brazilian energy system, and shows demand rising from 500TWh in 2010 to 1100 TWh in 2040, with natural gas and biomass generation expanding to meet much of this demand. Increases in these two sources are cost effective and widely expected [133, 184, 208].

The side cases were developed to represent sensitivity analyses aimed at assessing two specific energy technologies: hydrolysis for ethanol production and solar power. All side cases maintained the same demand growth to 1100TWh in 2040, shifting only the generation mix to meet demand. Two scenarios were developed for each technology, to examine a basic vs. intensive approach. The basic side cases were solved using the MESSAGE model, with the more intensive versions produced by magnifying the shift in per-source generation between the base case and the side case by a constant factor. In the first side case (BIO), an increase in second generation ethanol production from hydrolysis of sugarcane bagasse was forced into the model to assess the implications for decreased availability of biomass for electricity generation.

Table 34 depicts the premises about increase in ethanol production from hydrolysis in the BIO scenario. The hydrolysis case was magnified by 1.5 to produce the BIO2 scenario. This factor represents the maximum additional ethanol that can be produced from hydrolysis while maintaining zero or positive biomasse electricity production.

The second side case (SOL) evaluated the impacts of increased participation of solar energy in the electricity generation mix. A combination of solar electricity generation technologies were forced into the model, with cost optimization for meeting the remaining demand. In 2040, solar technologies were responsible for generating 4.0% of total demand. The technological alternatives were: concentrating solar thermal, CST with 12 or 6 hour heat storage (CST 12h and CST 6h), photovoltaic (Solar PV), solar and bagasse hybrid CST plants (Solar Hib). Table 35 shows the penetration of solar energy technologies in the SOL scenario. The SOL case was magnified by 2 to produce the SOL2 scenario, which generates 8.8% of electricity from solar technologies in 2040. This higher percentage would represent a more aggressive policy towards the use of solar power.

Table 12: Demand requirements during 2010 and 2040 for Brazilian scenarios

The business as usual (BAU) is cost-optimal, while the BIO and SOL side cases are cost-optimized outside of forced changes to biomass and solar usage. The BIO2 and SOL2 cases are magnifications of the difference between the BAU case and respective side cases to examine response linearity in the calculation model.

	2010	*2040*				
Source	**All**	**BAU**	**BIO**	**BIO2**	**SOL**	**SOL2**
Total Demand (TWh)	500	1,100	1,100	1,100	1,100	1,100
Coal	2.4%	2.9%	2.8%	2.8%	2.9%	2.9%
Natural Gas	15%	23%	28%	31%	20%	17%
Oil	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%
Nuclear	3.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Hydro	76%	61%	61%	61%	61%	60%
Biomass	3.2%	8.1%	2.9%	0.3%	8.1%	8.1%
Wind	0.3%	3.2%	3.2%	3.1%	3.1%	3.1%
Solar	0.0%	0.0%	0.0%	0.0%	3.7%	7.5%
Total	100%	100%	100%	100%	100%	100%

All three basic scenarios were generated using optimization for economic cost, with the basic side cases optimizing cost for all unforced generation requirements. The more aggressive side cases magnified the effects of the basic ones on per-source generation requirements. The initial and final requirements for all five cases are shown in Table 12. Both side cases are sensitivity analyses that were conducted in order to test alternative pathways for the Brazilian energy sector as the result of directed energy policies. The side cases differ from the reference case in that they are not least cost pathways, since they do not encompass the optimal solution for the evolution of the electricity sector. On the contrary, they are alterations from the least cost scenario built specifically to illustrate the potential and applicability of the LCA methodology by providing examples of how this model can be used to evaluate the results of energy policies directed at incentivizing specific technologies.

5.4 VALIDATION

Results were validated by comparing 2010 model results for GWP to World Bank data on GHG emissions from energy [135] and to GHG emissions calculated from the Brazilian Government's National Energy Balance (BEN)[216]. Values for both methods and model results are visible in Table 13; World Development Indicator data is available through 2008 and was extrapolated to 2010. The 2010 total value is from a World Bank report on low-carbon Brazilian land use and energy scenarios, and matches the sum of the three independent categories [217]. For a second reference/validation point, energy-related GHGs was calculated using emission factors and 2010 energy usage from the BEN. Electricity's GHGs were calculated using EIA combustion factors, which exclude any impacts from reservoirs. Finally, model results for electricity were reported with the average of the heating and transportation values from the two methods so that total energy-related GHGs could be compared.

The model results include indirect non-combustion emissions, increasing electricity GHGs in comparison to the two validation datasets. While reservoir emissions were included in the model, they were not compared during this validation phase, and were separated out for results reporting due to high uncertainty. The inclusion of separate values for the GHGs of tropical and temperate reservoirs produces a per-MWh value for hydropower of 50 kg/MWh and gross emissions from reservoirs of 18 Mt CO_2-eq in 2010. There is a clear need for further study of reservoir emissions (see Section 5.5.3 for further discussion), but not including some estimate of these emissions would be inappropriate due to their importance. Outside of hydropower's contribution, the model results are in close agreement with existing data for GHGs.

Table 13: Validation for the Brazilian BAU scenario (Mt CO_2-eq)

Source	*Year*	*Electricity*	*Heating*	*Transport*	*Total*
World Bank [135]	2005	59	34	136	229
World Bank LU, [135, 217]	2010	64	39	152	256
BEN Calculations [216]	2010	58 (EIA factor)	40	168	266 (EIA)
REWSS Model Results[1]	2010	68 5%: 50; 95%: 86	39	160	286

[1] The model factors for this work do not include impacts from hydropower reservoirs.

5.5 RESULTS

5.5.1 Base Case Impacts

Annual results in all five impact categories (GHGs, energy, water, land, and cost) under the base case (BAU) scenario for Brazil are shown in Figure 15. Values are shown on both an absolute and per-MWh basis, normalized to the 2010 values from the first year of model results. With total electrical demand increasing by a factor of two, impacts in all categories rise on an absolute basis by 2040. The largest increases are in GHG emissions and energy, with slower rises in absolute water consumption, land occupation, and economic cost, and decreases in the per-MWh values of these later three impact categories.

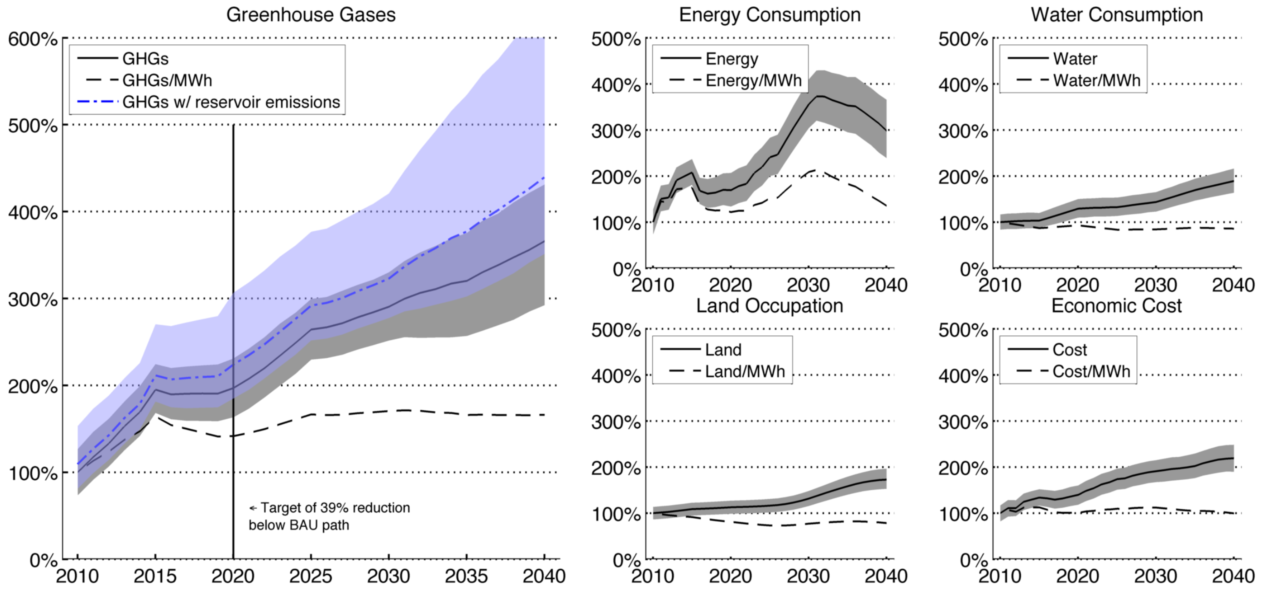

Figure 15: Annual results for the Brazilian BAU case.

Results are normalized by respective values calculated for 2010, with shading denoting a 90% confidence interval. Energy consumption refers to primary energy without the energy included in fuels. The line and interval for GHGs including reservoir emissions (shown in blue shading) show net emissions as 10%, 50%, and 90% of gross emissions.

GHGs are shown with emissions from hydroelectric reservoirs as additional impact, with large uncertainty. The midpoint shown here assumes that 50% of gross emissions from reservoirs are natural, leaving 50% as net emissions, while the shaded region demonstrates net emissions from 10% to 90%. This additional source of emissions represents a potentially large addition to existing impacts, but is associated with high uncertainty. The bulk of the emissions are from non-reservoir sources, with increases driven by fossil fuel usage, rising demand, and occasionally construction. With reservoir emissions included, there is the potential for later increases in GHGs to be driven by tropical hydropower.

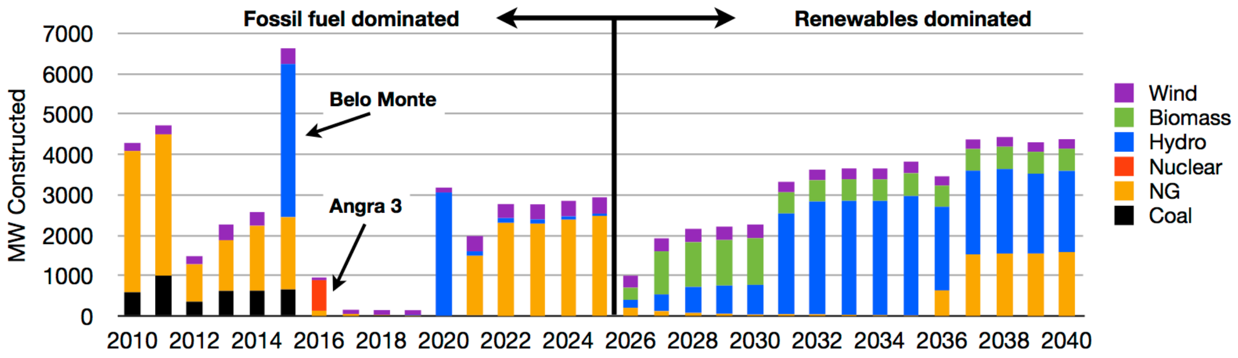

Figure 16: Average capacity constructed under the Brazil BAU case.

Figure 16 shows capacity additions for an average trial, divided roughly in half in terms of behavior. The first decade primarily expands natural gas, with some known construction of nuclear and hydro and a small expansion of coal-fired generating capacity. Natural gas is currently used as a peaking fuel to allow optimized hydropower generation. Going forward, an increasing amount of NG capacity is expected to be used for dedicated baseload power. The small amount of additional coal capacity is a primary driver of GHG intensity - a problem discussed further in Section 5.5.2. The hydropower capacity added during this time is from projects in progress such as Belo Monte. The known projects provide enough supply that little extra capacity is required from 2016 to 2020, resulting in a decrease before another round of NG additions. Small amounts of wind are added throughout the entire scenario as the demand increases continually on both an absolute and percentage basis.

The second half of the scenario shifts from adding NG to adding hydropower and more biomass capacity. It is expected that simple conversions of existing capacity will enable biomass generation up to 2025, but afterwards new capacity is required in our model. The hydropower capacity is expected to be built primarily in the Amazon, as high-quality dam sites outside of the tropical zones have mostly been utilized. The lower capacity factor of these tropical dams requires more capacity for the same amount of generation, along with a higher propensity for methane generation. The higher per-MWh GHG intensity from these dams relative to southern boreal dams doubles the fraction of GHGs from hydropower and increases the per-MWh intensity by a factor of four by 2040 when reservoir emissions are included. Dams are also responsible for the peaks in 2015 and 2031 seen in Figure 15 in energy consumption. The two peaks correspond to initial construction of Angra 3 and Belo Monte during the mid-2010's, and a large addition to hydroelectric capacity in the 2030's. Long term increases in non-construction energy intensity are attributable to increased use of natural gas, which has the highest individual MJ/MWh intensity [173]. Increased use of LNG would further increase energy consumption/MWh, a case not examined in this work.

Water consumption and land use follow similar paths, driven by inertia from and changes to hydroelectric generation, particularly in the later half of the time period studied. The impact factors for water consumption and land use are an order of magnitude higher for hydroelectricity than for other sources, and the existing dominance of hydropower dampens impacts shifts that result from the use of a more diverse generation mix. Both impact categories show a decrease in per-MWh impacts over the course of the scenario as a more diverse generation mix allows new generating capacity without significant increases in water consumption or new flooded land. The slightly larger increases during the final decade are associated with the late build-out of Amazonian hydroelectricity, which will likely create larger reservoirs and associated increases in evaporation.

5.5.2 Carbon Commitments

Total GHG emissions from electricity rise to 360% of its 2010 value by 2040. This rise is driven by several factors, as described above, and may make existing and potential carbon reduction commitments more difficult to meet. Brazil has a national goal of reducing its national carbon footprint by 39% relative to a BAU pathway by 2020, and a target of reducing deforestation to 3925 km^2/yr, down from historic rates of 10k-20k km^2/yr [218, 219]. The BAU pathway, designated in 2007, is based on potential increases from 2005 emissions, and allows an increase of ~33% over actual 2010 emissions while still meeting the 39% reduction goal. This increase, from ~1500 Mt CO2-eq to 2080 Mt CO2-eq, will be dominated by increases in emissions from energy, industry, and agriculture, with additional space provided by continuing decreases in deforestation. With 2010 deforestation of 6450 km^2 [219], meeting the 2020 deforestation target will result in a decrease of 39% in land cleared, and a 27% reduction in carbon emissions overall relative to 2010, assuming average per-acre impacts. This provides space for a 60% increase in emissions from sectors aside from deforestation.

The results of this work suggest, however, that increases in electricity-related emissions will increase by 98% from 2010 levels by 2020, without considering emissions from hydropower plants' reservoirs. Meeting the emissions target with this increase will require slower growth in emissions from other sectors such as transportation, industry or agriculture. The results suggest that meeting Brazil's carbon targets may require additional effort beyond current plans [220]. In addition, current estimates of carbon footprint do not take reservoir emissions into account because of the large inherent uncertainties [221]. If these impacts are included, electricity's GHGs may increase by 8-48% in our model. The rise in electricity-related GHGs is expected with national development and an associated increase in per-capita energy use, but would make it more difficult to find sufficient reductions to meet stated greenhouse gas emissions targets. The continued rise in the second half of the scenario support a cautious view of the achievability of future carbon emissions targets by Brazil, particularly as deforestation declines as a percentage of emissions while energy and electricity increase. Identifying the best approaches to avoiding these issues is done using a decomposition approach in Section 5.6.

5.5.3 Tradeoffs from Renewables

Brazil’s low GHG intensity for electricity has been enabled by use of its plentiful renewable resources, which have been assumed to have no to low emissions - both hydropower and biomass. The move towards increased use of natural gas and tropical hydroelectric dams will unavoidably increase GHG emissions. Recent evidence around tropical reservoir emissions continues to support this claim though, as discussed below, much more work is still needed [198, 205].

Hydropower has provided Brazil with a large amount of energy and the ability to grow its economy, all with lower GHGs than the fossil fuels used to energize development in much of the rest of the world. These benefits have come at the cost of significant and often unmeasured ecosystem impacts. Water consumption is used as an ecosystem metric in this model, and is understandably high for hydropower, but evaporation is only a small piece of overall impacts. Land occupation helps to capture impacts to potential or existing communities, but is again a proxy for more complex impacts. Issues such as biodiversity, and species migration, or social impacts to surrounding communities lack comprehensive or widely accepted methods for measurement and incorporation into life-cycle studies. Further, though reservoirs are acknowledged as a net source of methane relative to the ecosystem present before the dam, the connection between gross and net emissions is unknown, and, along with land occupation, is likely to have significant variation from dam to dam. While tropical dams have the potential to flood more land per unit of capacity, environmental regulations make it unlikely that they will be built as such. The information used in this model is the best available but still represents less than 15 dams. The use of Monte-Carlo methods incorporate this uncertainty, but better information is still necessary to refine estimates or include more direct impacts. The lack of information shows a need, particularly for Brazil, for increased measurements and work so that models such as this one can be more inclusive and inform better decisions about including hydropower and other sources as part of powering sustainable development. Particularly alarming in light of these higher impacts from tropical reservoirs and their role in our results is the inclusion of hydro projects in Clean Development Mechanism (CDM) projects aimed at reducing carbon emissions [222]. The tradeoffs between GDP, GHGs, and ecosystems must be considered in light of sustainable development goals, balancing additional electricity off of ecosystem and community damage and likely increases, rather than savings, in GHGs.

One proposed alternative to hydropower would be an expansion in solar power in addition to the wind power expected by the MESSAGE scenarios, or the production of additional ethanol from biomass via hydrolysis rather than producing electricity, possibly as a more effective utilization. These alternatives were explored via the side cases from the BAU case, and cumulative results can be found in Figure 38. The results show limited change and more tradeoffs. Switching the use of biomass from electricity to additional ethanol has negligible changes to GHGs when the avoided emissions from oil are considered. The other categories show drops in land occupation and water consumption, similar energy consumption, and higher cost, none of which include offsets from ethanol. Although the savings from not producing oil may reduce the extra cost of the biomass side cases, processing biomass to hydrolysis will require more water and energy than combusting it for electricity, possibly outweighing any gains in those areas. In the solar cases, overall GHGs are reduced at the price of higher - but uncertain - energy consumption during construction, and likely higher costs. Some land savings occur, but the low energy density of solar minimizes savings over hydropower.

The side cases show that, regardless of the sources chosen, attempting to maintain a low per-MWh GHG intensity through the use of other renewables will incur impacts in other categories, and continuing to rely on hydropower may result in higher impacts in all categories. In many ways, even with high uncertainty, GHGs are one of the best studied impact categories. While our results show that scenarios and existing data can help examine impacts and future trends, these tools will remain incomplete until more data exists on net emissions from reservoirs, and some data exists for broader ecosystem impacts from all renewable sources. This information is necessary to guide good policy-making for more sustainable development.

5.6 CONCLUSIONS

Brazil has unique power generation characteristics because of the amount of hydropower and the use of on-site sugarcane bagasse. Brazil’s future development will require additional electricity, which is likely to come from a more diverse set of generation types. With the supply-side trajectory projected for this work, the results indicate that Brazil may have more difficulty meeting carbon targets because of increased electricity-related GHG emissions. Identifying ways to change GHG emissions requires factoring impacts into metrics such as per-capita electricity use or impacts per unit electricity. Emissions intensity per MWh at the start of the BAU scenario is 172 kg CO2-eq/MWh, significantly lower than the U.S. average of 748 kg CO2-eq/MWh [136]. Per-capita electrical demand is also much lower for Brazil than the U.S., at 2.4 vs. 14.2 MWh/capita in 2010 [135]. Going forward, the BAU scenario shows GHG emissions intensity growing by 47% by 2020 and 82% by 2040, with per-capita electricity demand growing by 28% by 2020 and 89% by 2040, after adjusting for projected population growth [223]. Other impact categories show smaller increases or decreases in intensity, but grow on an absolute basis because of increases in population and per-capita consumption.

Maintaining a relatively low-carbon electricity supply requires efforts on both supply-side emissions intensity and per-capita demand. In the short term, addressing emissions intensity suggests avoiding growth in coal-fired generation, as increases in the use of coal are a primary factor in the early rise in carbon intensity during the mid 2010s (Figure 15 & Figure 16). Avoiding additional infrastructure and use of coal while it remains a small portion of the generation mix prevents future challenges in shifting away from coal. Over longer time scales, avoiding natural gas through increased hydroelectric generation may enable emissions intensity to remain low - though there is large uncertainty in this area - at the cost of increased water and land related impacts, as well as increasing public protest. Avoiding natural gas in general may be difficult due to a lack of easily scaled generation options - there is a finite supply of bagasse, and nuclear plants likely cannot be constructed in time to meet 2020 goals, though they may be an expensive option for longer-term objectives. Solar and wind remain as possibilities for reducing emissions intensities, though they will incur larger capital costs than NG and are similarly low-density in land occupation as hydropower. Brazil's efforts to expand wind are ongoing and may be key to maintaining low GHG emissions intensity.

In addition to supply-side policies and changes, reductions in demand - beyond the MAED model predictions that this work is based on - may be sensible. Without compromising quality of life, there are likely efficiencies that can be implemented in industrial processes, as identified by the World Bank [217] . If these efficiencies are insufficient and climate change goals hold enough significance, reductions in per-capita demand through conservation would be required. Because of variations in development between major cities and some rural areas, conservation in some regions could allow others to continue increasing consumption while still reducing per-capita electricity consumption for the country as a whole. Combinations of supply- and demand-side approaches, based on perceived feasibility, can easily be tested using the model presented in this work.

Hydropower plays a central role in Brazilian electricity, but the impacts of future dams are very uncertain. Data on ecosystem impacts beyond GHGs is sparse, and uncertainty about net GHG emissions and land usage from tropical hydroelectric reservoirs may reduce viability of expanding hydroelectricity. Hydropower in Brazil is an excellent example of model outputs as well as the absence of data informing a need for future work.

The underlying model in this work allows the examination of life-cycle impacts, major impact drivers, and infrastructure construction on an annual basis, rather than at scenario endpoints. The presented results discuss electricity for a single region, with a focus on GHG emissions, but the model has the potential to assess broader questions in other regions. Future work could expand upon this model, adding data and calculations for energy use in transport and heating, as well as impacts from water and wastewater treatment. These additional classes of demand can allow the examination of questions about the use of new energy sources such as shale gas, interconnections between energy and water supplies, or the lowest-impact options for shifting away from non-renewable sources. With an increasing set of jurisdictions around the world investigating the environmental impacts stemming from energy supplies, quantitative tools such as this model can play a critical role in understanding and developing policies and scenarios to meet both environmental and economic goals.

6.0 APPLYING THE REWSS MODEL: PENNSYLVANIA AND ARIZONA

6.1 REGIONAL MODELING APPROACH

For US regions, most LCA data is applicable to existing technology or measured for technology in development. For renewables that are geographically dependent, information from NREL is available at a range of resolutions to help identify state potentials and likely capacity factors [181, 188]. No assumptions or approaches beyond those described in Chapter 4 were required, as the REWSS model is constructed with the US in mind, incorporates regional conditions from user input and requires little additional adjustment. It was assumed that technologies (aside from renewables) performed similarly in all areas, allowing the use of a generic set of LCA impacts. A full list of LCA data sources is available in Table 36, and the input information for the PA and AZ BAU scenarios is available in Appendix D.

6.2 PENNSYLVANIA'S ENERGY FUTURE

6.2.1 Scenarios Examined

The rise in unconventional as production from the Marcellus Shale has provoked many questions not only about the safety and impacts of individual wells, but also about large-scale energy policy and the use of the NG. A key decision is whether NG will be used as simply to replace coal, or as a way to quickly reduce dependence on coal as part of a transition to renewable sources. All of these pathways can be helped or hindered by policy decisions, and so this work focused on three major scenarios, testing each one's overall impacts and sensitivity to initial assumptions.

The base case scenario used the national energy pathways and demand projections of the EIA's AEO 2013 as a guide for electricity, transportation, and heat, and models a Business As Usual (BAU) scenario. This base includes federal policies such as the Renewable Fuels Standard around biofuels. Also inclued were intended plant retirements, primarily coal plants, whose section of demand was distributed among current sources based on the generation mix during the year of retirement. PA's alternative energy portfolio (AEP) standard has two tiers, one for non-conventional hydro and biomass, and one for solar, wind, and geothermal technologies. The standard also sets a minimum percentage for solar by itself. PA's biodiesel usage going forward is based on in-state production, with current requirements at a 2% blend. Water demand and source mix in 2010 was taken from USGS estimates, which have remained nearly constant over the last 20 years [3, 224]. Wastewater demand and source mix were taken from the EPA's Clean Watershed Needs Survey from 2008 [196]. Both water and wastewater demand were assumed to remain constant on a per-capita basis, as PA shows little overall water stress or focus on conservation [115]. Wastewater treatment technologies, following the CWNS requirements, showed small shifts towards advanced treatment options.

Region specific options for various sources were included. Because of PA's plentiful surface waters, more power plants use open-loop cooling, which consumes less water but withdraws more. 90% of coal used for electricity was assumed to come from underground mines typical of the Appalachian region. For biofuels, ethanol was assumed to come entirely from out-of-state corn production, based on EIA data on ethanol production capacity, and used a national average for irrigation rates. In contrast, 95% of biodiesel was modeled as produced from non-irrigated crops. This 95% was estimated by noting that 42 Mgal of biodiesel were produced in PA in 2011 [225], where irrigation of feedstocks is uncommon [226]. PA's requirement of 2% biodiesel in all transportation diesel fuel requires 31 Mgal [227], suggesting that in-state production is more than sufficient to meet demand, even with some situations where higher percentage blends are used. 95% was used to allow for some irrigated crops, either produced outside the state or due to dry periods during the growing season. The remaining 5% was modeled using national average irrigation rates and not attached to a particular location. Future additions to biodiesel supply were assumed to be 25% from irrigated feedstocks, based on constant year-over-year production in PA from late 2010 to early 2013. All biodiesel consumption was assumed to be soy, the most common first-generation biodiesel feedstock. Advanced options such as algae are available using pre-commercial impacts, but were assumed to make up a negligible fraction of total consumption for all three cases due to a lack of data on future penetration or commercial-scale impacts.

Building off of this BAU case, two alternative scenarios are particularly intriguing. The first side case (Marcellus SHale, MSH) focused on the widespread use of natural gas, in light of its local nature and currently low price. This scenario represents the vision from current PA Governor Tom Corbett, and an initial set of incentives would include PA's recent Act 13 incentives for NG vehicles [228]. The basic trends for energy sources were still based on the BAU case, but changes in all energy categories were adjusted to *emphasize natural gas and minimize increases in coal and petroleum*. This was done by changing $p_{s,p}$ (Section 4.2.1) to 3 for all NG sources, and 1/3 for all coal and petroleum sources. Sensitivity analysis examined the effects of shifting these parameters on total output. In addition, for electricity, retiring coal plants were replaced with NG rather than with a mixture of all sources. It was assumed that 70% of new NG-based energy consumption used gas from the Marcellus Shale. Marcellus specific impacts were based on the work described in Chapter 3 of this document. Water demand was again based on constant per-capita demand, with a slight increase in industrially treated wastewater to account for increased drilling, and an assumption that flash evaporation was used for treatment [45]. While not inhibiting the growth of renewable technologies, this scenario also had no emphasis on them, leaving them to grow with national trends. No long-term goals for renewables were set beyond the existing AEP.

The second side case (RENewables, REN) emphasized renewable technologies, with a limited shift towards NG as a replacement for retiring coal plants for the first decade. The long-term trends and preference for renewables make NG more of a ‘transition fuel’ than a long-term baseline source, a common discussion point for energy policy. Other renewable energy sources such as electric cars and biomass heating can also be emphasized.As with the MSH case, the primary shift was in shifting the preference factors for specific sources to magnify changes by a factor of three. For transportation, $p_{s,p}$ for ethanol and biodiesel was set to 1 while petroleum was set to 0.33. Biofuels have seen a decline in policy support for corn ethanol and uncertainty about economical supply of cellulosic ethanol, and are generally sold in conjunction with petroleum, but remain as a renewable technology. In addition to these preference changes, the current AEP state policy was extended through 2035 with the same two tiers and rate of growth.

6.2.2 Results

The BAU results for PA show a few key shifts in the next 10 years, and a slow or negligible shift in impacts to 2035. Results in each impact category are shown on an annual basis in Figure 17, along with a 90% confidence interval. Cumulative impacts for the three scenarios are compared in Figure 18, and absolute impacts are shown in Table 37, Table 38, and Table 39 in Appendix D. GHG emissions, energy consumption, and cost all remain fairly constant over the course of the scenario, with an initial drop in GHGs. Land occupation and water consumption more than double, again changing mostly near the start of the scenario. Most of the changes are the result of ongoing shifts towards replacing some percent of current infrastructure with alternatives. For electricity, this manifests in the use of natural gas instead of coal, while for transportation biofuels take the place of petroleum.

The long-term impact pathways are relatively static. The state AEP ends in 2025, and no follow-on policy was assumed for the BAU case. PA is also projected to have a static or slightly declining population through 2040 [180], with minimal changes in per-capita demand expected. The AEP drives initial growth in renewable energy, providing a basis for following national trends, but it is insufficient to drive change to GHGs, and has negligible impacts to other impact categories – coal retirements and the profitability of wind energy with federal tax credits account for most of the changes.

Regardless of policy changes, results indicate that renewables, particularly biomass and wind in PA, will expand to provide ~20% of the overall electricity mix. Similarly large gains in the use of renewables for transportation and heating are not seen because REWSS follows scenario trends while meeting regional policy, rather than actively identifying a path. Because the conservative AEO scenario does not show large changes to either source mix or total demand for transportation and heating, even a large preference for renewables does relatively little to shift them.

Water and wastewater impacts comprise a small fraction of all five impact categories with a maximum combined fraction of 6% in costs and 1-3% in all other categories. In a state with plentiful water supplies, less effort is required to provide water, as well as the two categories being on different scales normally – critical and interconnected, but with impacts dominated by energy. This aligns with history, where energy has been the limiting factor for civilizations – the impacts and, by proxy, effort, required to supply water is minimal when compared with that necessary to provide energy, particularly for demands in modern developed countries.

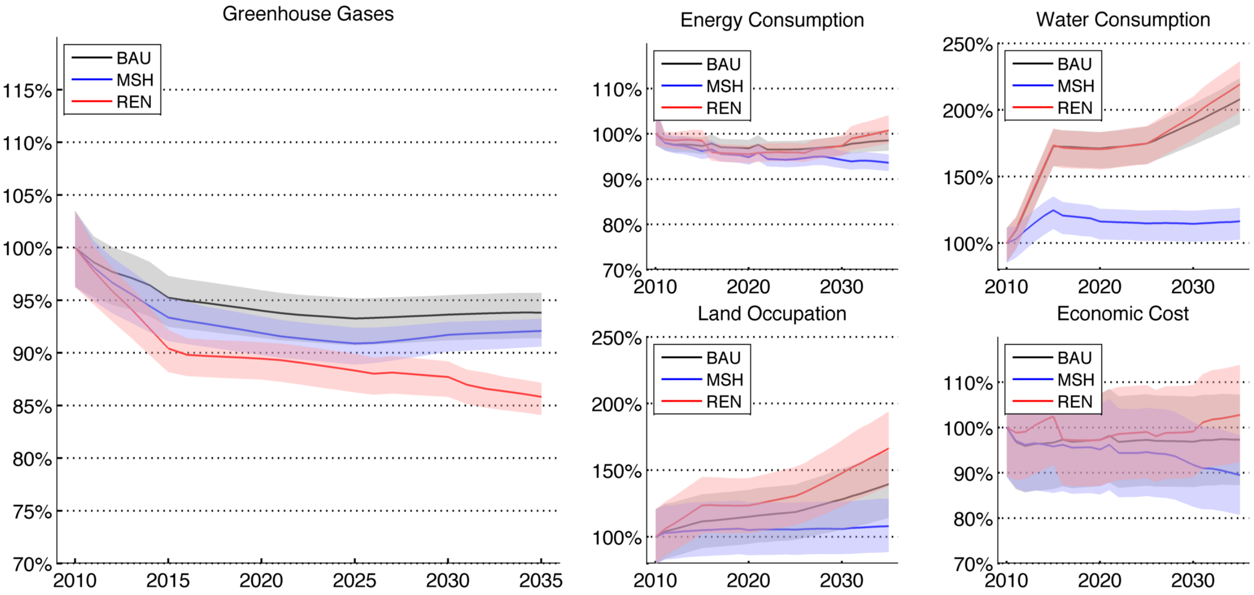

Figure 17: Annual impacts for Pennsylvania scenarios

Impacts are shown normalized to model results for 2010. Shading denotes a 90% confidence interval.

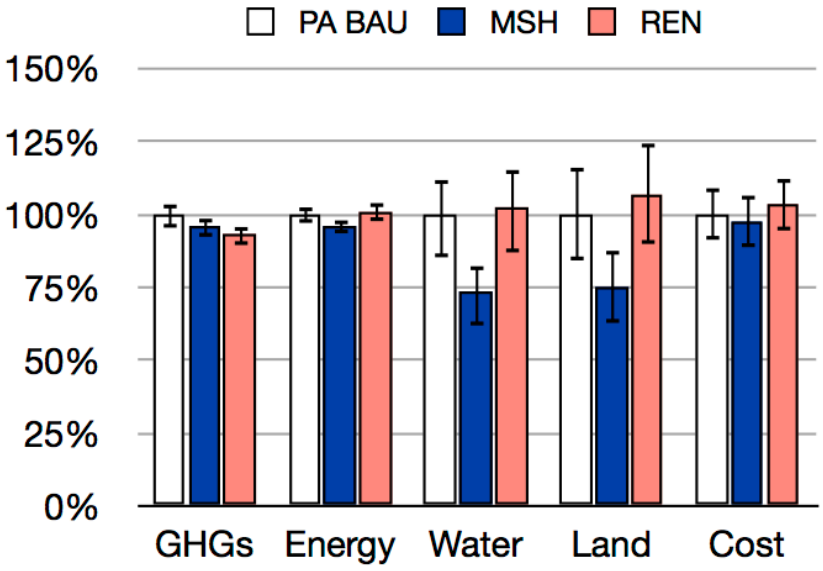

Figure 18: Cumulative impacts for Pennsylvania scenarios

Impacts are normalized to BAU scenario. Land occupation considers total area without accounting for length of occupation.

6.2.2.1 Greenhouse Gas Emissions

GHG emissions show an initial decline as several older coal plants retire and the use of oil for electricity is phased out. It is also likely, though not explicitly modeled in the BAU case, that new EPA regulations will limit the construction of new coal-fired capacity. The replacement for coal-fired capacity is largely natural gas, along with biomass and wind. By the end of the BAU case, NG provides 17% rather than 13% of electricity, and wind provides 9%, rising from 0.5%. Coal retirements account for the short-term GHG drop overall, with longer-term generation mix stablizing GHGs at 93% of their 2010 value. Much of the stabilization is a result of minimal change in GHGs in transportation and energy, which act as a buffer to larger-scale reductions. The conservative nature of the AEO scenario is also a factor.

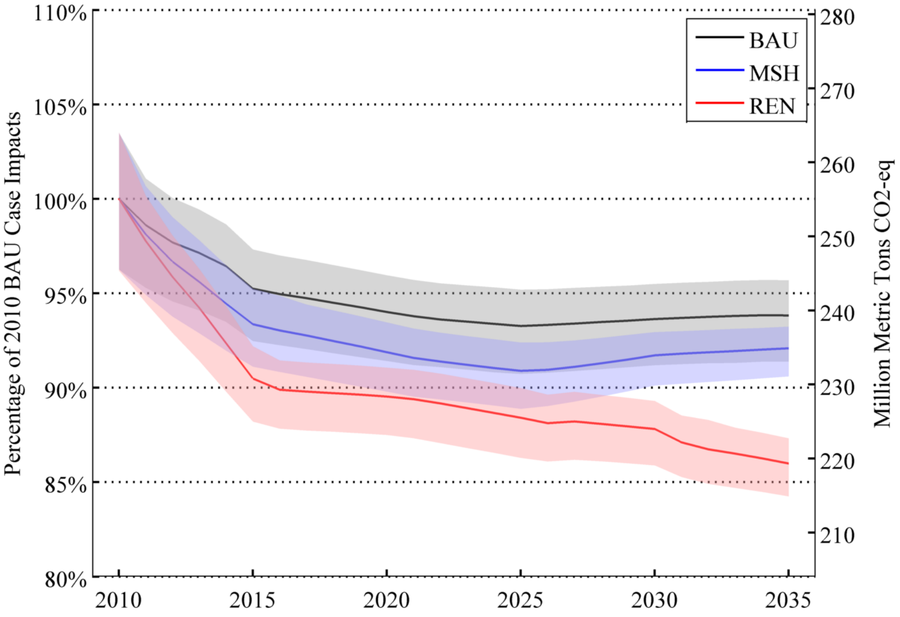

Figure 19: Annual GHG Emissions for PA Scenarios

The use of the MS as a replacement for coal-fired electricity and petroleum-based vehicles helps expand the initial drop in emissions, but shows little long-term effect. This lower plateau shows the limits of NG as a long-term solution, with a maximum reduction in GHG emissions of 40% of coal's source fraction, and 20% of petroleum's. NG replaces an additional 15% of coal-fired electricity in the MSH case relative to the BAU case (Table 14), for a net reduction of 21% x 15% x 40% = 1.3% of state-wide annual GHG emissions. The 20% of transportation energy supplied by NG in 2035 adds an additional 39% x 20% x 20% = 1.6% from reduced petroleum usage. If all coal and petroleum were replaced with NG, the maximum annual reduction would be (21% x 31% x 40%) + (39% x 90% x 20%) = 10%. The cumulative savings in GHG emissions between the BAU and MSH cases are 2%, underlining the need to look at the MS from a broader perspective and consider the overall effect on state impacts rather than the relative impacts of NG and other fuels. While NG is cleaner burning for many particulate emissions [35], the potential gains from widespread use of the MS are smaller than might be expected or desired.

If renewables are emphasized rather than NG, GHG emissions drop further, with cumulative savings of 5% between the BAU and REN cases. The continuous shift towards renewable sources also maintains a downward trend in overall emissions, reaching a 13% reduction in 2035 expected emissions relative to 2010. The increased slope during the final five years is a result of national trends towards solar and wind energy. Even though this case shows more than twice the cumulative savings, it is important to consider that a ‘sufficient’ pathway would suggest a 44% drop in annual emissions by 2020, with a 95% drop by 2050 [229]. Under a linear decrease to that point and a subsequent plateau, cumulative emissions would be reduced 46% from the BAU case calculated here. Clearly, none of these three scenarios will produce sufficient GHG emissions reductions, and more attention to transportation and heating energy will be required. In addition, demand-side actions, both efficiency and conservation, could improve the outlook of these scenarios. Demand-side actions are underway in PA for both policy and economic reasons, but hypothetical options were not modeled here to maintain the same demand levels across supply scenarios and facilitate comparison. For more information, see Sections 6.2.3 and 7.3.

Table 14: Energy source mixes for PA scenarios

	PA All	*PA BAU*	*PA MSH*	*PA REN*
Source	**2010**	**2035**		
Coal	44%	31%	17%	20%
NG	15%	19%	38%	10%
Oil	0.46%	0.0%	0.0%	0.0%
Nuclear	33%	28%	24%	30%
Hydro	2.5%	2.6%	2.2%	7.7%
Biomass	3.24%	10%	9.3%	10%
Wind	2.45%	8.7%	8.3%	18%
Solar	0.04%	0.82%	0.7%	3.8%
Geothermal	0.00%	0.00%	0.0%	0.5%
Petroleum	95%	90%	74%	90%
EtOH	4.0%	4.8%	3.7%	5.0%
Biodiesel	1.2%	4.9%	2.1%	5.1%
CNG	0.00%	0.00%	21%	0.00%
Hydrogen	0.00%	0.00%	0.0%	0.00%
Electric	0.00%	0.000001%	0.000001%	0.15%
Coal	19%	23%	20%	21%
NG	58%	56%	61%	56%
Petroleum	17%	15%	14%	14%
Biomass	5.6%	5.6%	5.7%	8.5%

6.2.2.2 Energy Consumption and Economic Cost

The two impact categories without smooth paths are energy consumption (Figure 20) and economic cost (Figure 21). Both of these are sensitive to construction occurring. Energy and water infrastructure is capital intensive and relatively low-energy during operation, such that initial construction accounts for a relatively larger fraction of life-cycle impacts. Energy shows small peaks when rapidly constructed capacity – transportation, heating, and some renewable electricity sources – are added, and longer term humps – such as from 2012 to 2016 under the REN case – when longer-term construction or ongoing build-up of a particular source occurs. The 2012 to 2016 bulge is a result of electric vehicle construction, and longer-term construction's impacts are visible in Figure 15 for Brazil.

With a shift towards renewables at some level in all three scenarios, a decrease in primary energy might be expected as the extractive supply chain is no longer necessary to provide fuel.

However, transportation is responsible for 70% of energy consumption under all three scenarios, with upstream impacts from resource production accounting for 78% of this fraction. Transportation shows only a 5% shift away from petroleum over the course of the scenarios (Table 14), leaving the majority of primary energy consumption unchanged. The use of low-EROI biofuels does not improve the situation. For primary energy consumed for electricity supplies, the resource production stage is responsible for 62% of the total, but decreases by 30% from 27 PJ in 2010 to 19 PJ in 2035.

Cost impacts show the same types of peaks, but with significantly more uncertainty. Because cost is not a physical property of the technology, it is more subject to change and thus a wider range is used for the underlying LCA data. In particular, the costs of some technologies could increase (e.g. carbon pricing) or decrease (e.g. recent photovoltaic panel prices) beyond inflation. Under these predictions, NG is relatively inexpensive and renewables have a cost premium. The MSH case shows lower costs, but if NG prices increase faster than other energy sources, the relative costs of the three scenarios could shift.

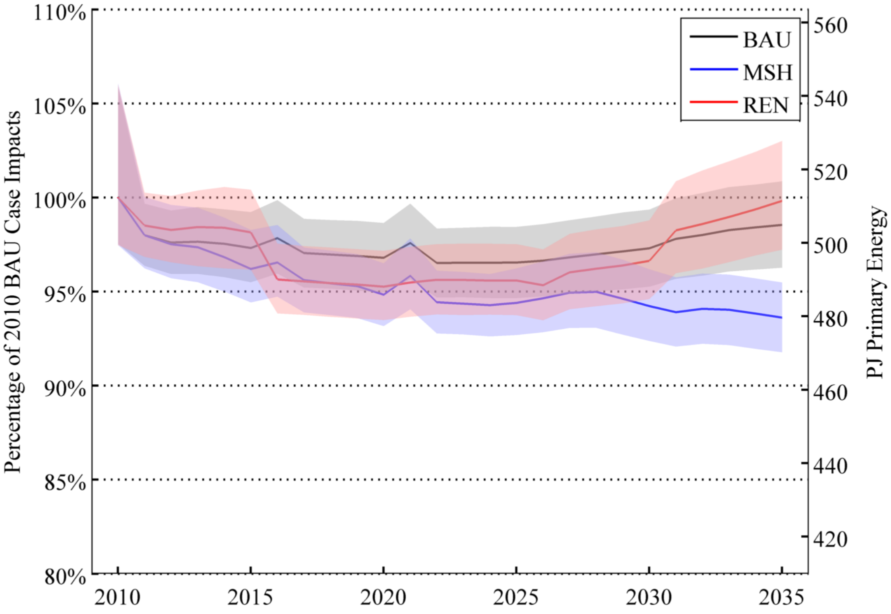

Figure 20: Annual Primary Energy Consumption for PA Scenarios

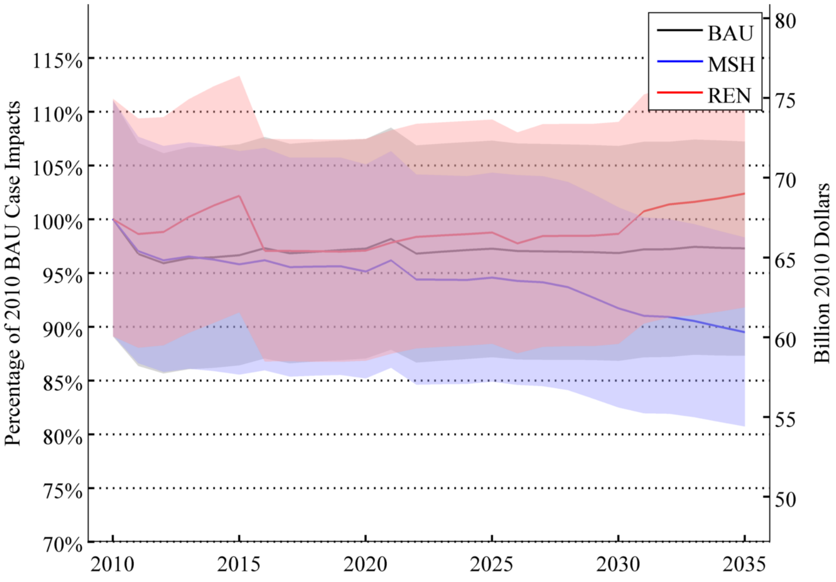

Figure 21: Annual Economic Cost (2010 $) for PA Scenarios

6.2.2.3 Water Consumption and Land Occupation

Water consumption (Figure 22) and land occupation (Figure 23) show the largest increases of the five impact categories, with BAU impacts reaching 210% and 140% of initial values by 2035. The key driver of these changes is the increased use of biodiesel and corn ethanol as part of national trends. Water consumption is primarily external, allocated from the regions where soy and corn are grown using irrigation. Importing biofuels from irrigated feedstocks is importing water against a gradient – moving it from a place where water is less available to one where it is relatively plentiful. The reason that this situation still exists is partly that water is not seen as a traded commodity, and partly that large areas of land are required. Biofuel crops are responsible for 90% of the 8-12 thousand km^2 of land occupation required for total energy and water supplies. Shifting to other sources of fuel could reduce both of these impacts – possibly with other tradeoffs – and avoiding irrigated feedstocks can reduce water consumption, though this consumption is upstream and not often visible to or controllable by the final user. Later generation feedstocks such as switchgrass for ethanol or algae for biodiesel may also have lower water and land requirements, but so far have not found commercial-scale feasibility, in part due to low EROIs [230].

The largest changes between the three scenarios occur in water consumption and land occupation, and are driven by greater or lesser utilization of biofuels. Although many of these impacts occur outside of PA, they are still allocated to where demand occurs. The fraction of transportation energy from biofuels in the MSH case is half that of the BAU case, and a slight 5% higher in the REN scenario. The lower usage of biodiesel under the MSH case produces the much lower water consumption seen in Figure 22. Soy is a water-intensive if common crop, even relative to other biofuel feedstocks [231] and other biodiesel options may reduce the sensitivity of model results to biodiesel usage. Land, in contrast, has similar impacts for both corn ethanol and soy biodiesel, and the gaps between scenarios are dependent on ethanol as well as biodiesel.

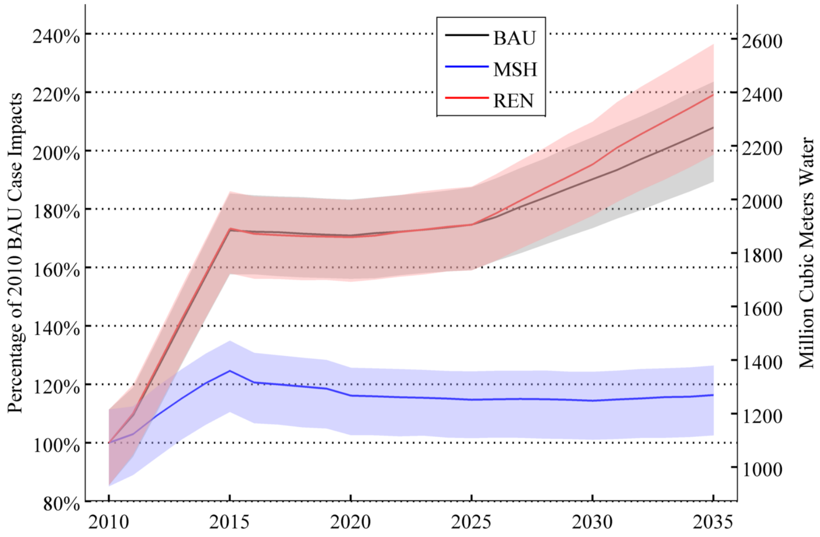

Figure 22: Annual Water Consumption for PA Scenarios

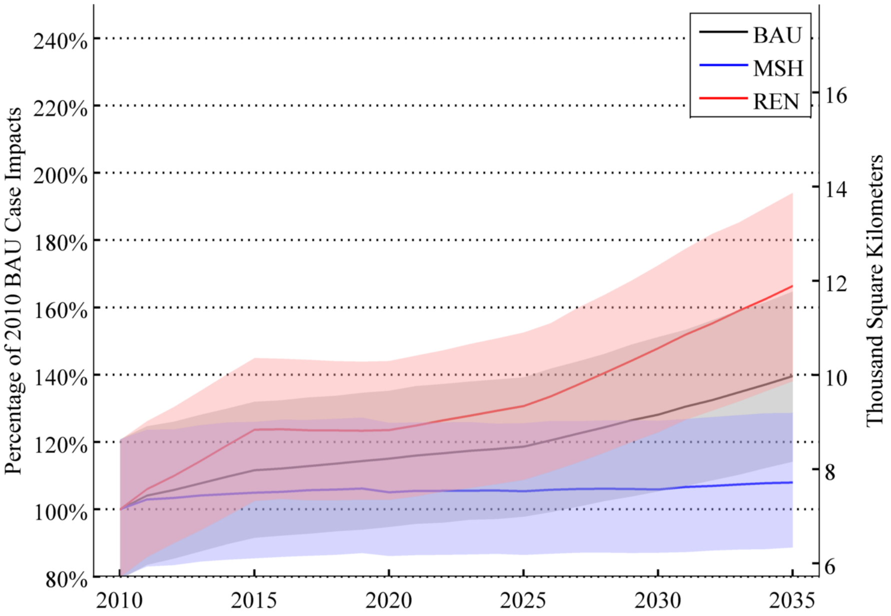

Figure 23: Annual Land Occupation for PA Scenarios

6.2.2.4 Energy-Water Connections

Results suggest that PA does not have an overly stressed water-energy nexus. In the BAU case, 1.9% of water withdrawals are consumed for supplying electricity (WfL), and 1.4% of electricity is used to supply water (LfW). The low LfW value results from plentiful supplies of local water, requiring minimal pumping. Water quantities are not a common concern in PA, and the LfW remains constant over the course of the scenario. Energy used on the demand side, such as heating water, is not directly included in this analysis (as per boundary conditions in Figure 4). The water consumed for electrical production is similar to the national average, but slightly lower due to a higher use of open-loop cooling, which withdraws large amounts of water per unit of energy but evaporates only a small fraction of it. The thermal pollution that can result from open-loop cooling could be measured by water quality metrics in future work (Section 7.3).

Water-energy connections shift if expanded to include all energy rather than just electricity. While EfW decreases to 0.5%, WfE rises to an average of 15% of water withdrawn. The primary driver of this rise is biofuel usage, which represents over 70% of in-system water consumption impacts 2035. It was assumed that most biodiesel for PA would be made from soy, which has been shown to have a high water footprint from irrigation. Because PA used only 0.3% of its water withdrawals for irrigation in 2005 [3], in-state production of biodiesel was assumed to have minimal water consumption. Ethanol usage also drives water-energy connections, with impacts largely outside of the region from corn crops, some of which are irrigated. This supply chain effectively imports water into PA in a manner that may run against a water scarcity gradient – places with less water using it to grow corn and sending it to places with plenty of water but little available land. Whether this situation is feasible in the long term is questionable, but problems with corn ethanol have been identified by many sources and its usage may fade and be replaced with a different crop. The use of irrigated biomass for any energy service, however, will incur a large impact to water consumption and the creation of a strong connection between energy and water.

PA's connections between energy and water do not shift signficantly for the alternative scenarios. The Marcellus Shale has received copious media attention around water demands for hydraulic fracturing, and these are included in the MSH scenario. However, as in previous studies, the increase in water requirements relative to the state as a whole is negligible [45]. Water *quality* remains in question. In addition, NG-fired power plants are likely to be more efficient and consume less water for cooling. Concern is still warrented around local water supply issues at the subbasin level, as well as risks to water quality from leaks and spills. Because the MSH case replaces 20%% of transportation with CNG vehicles, it reduces the usage of biofuels, dropping WfE to 9.8% from 15%. This tradeoff is not necessarily more sustainable – higher connections between water and energy are possibly sustainable depending on the sources of each, but higher usage of non-renewable fuels such as NG is, by definition, less sustainable (see Section 1.2). Energy demand for water shows no change in either alternative scenario for PA – the extra wastewater treatment required in the MSH case is similarly negligible.

In the REN case, the marginally higher use of biofuels shows no change to WfE. The REN case takes a neutral approach to biofuels, and an active prioritization would increase WfE. Higher water requirements could be indicative of a loss of extra capacity for energy supply in a more resource limited world. As an example, if EfW and WfE were both 20%, it is still possible for the WEN to be sustainable, but less energy and water would be available for final users. The BAU and REN cases caution against using biofuels without considering their additional water and land footprints, but show a stronger interconnection rather than infeasibility.

6.2.2.5 Sensitivity of Results

The scenarios examined are based on shifting many parameters, and are not useful if the conclusions on appropriate sources and likely shifts in impacts relative to the BAU case are not robust. To examine sensitivity, scenarios were evaluated with several individual conditions. First, the scenarios were modeled using electricity trends from the combined RFC-East+West power grids rather than the entire US, to test whether more regionally-focused trends with lower growth in renewables would reduce their utilization. Second, the preference parameters were varied from their default value of 3 or 0.33 over the range of 1-9 and 1-.11, respectively, while keeping other changes such as additional policies or capacity in place. Third, these preferences were separated, generating scenarios where only positive preferences were included or only negative preferences, where the full scenario does both simultaneously. This test helps to examine whether focusing on one class of sources is sufficient to drive change.

Electricity, because of the power grid, does not have its source mix as bound to geography as other classes do. PA is a net exporter of power, allowing the assumption that state capacity describes impacts, but a key piece of assessing the robustness of results is to examine the effects of modeling electricity using either the trends or source mix for the state. Modeling the BAU scenario using the trends for the combined RFC-East and RFC-West regions shows a <1% change in cumulative impacts in all categories, suggesting that national trends are a reasonable substitute. With the source mix from the RFC East+West region, PA's GHG emisisons intensity on a per-MWh basis would increase by 6% based on 2009 eGRID data [183]. However, with demand remaining the same, while PA's allocated impacts would be higher, other states, such as Indiana, would show lower impact intensity. The shift may represent a more accurate allocation in the absence of knowledge about imported and exported electricity, though the difference when other demand classes are included drops from 6% to 3%. This increase would also apply across all scenarios, making it unlikely to change the relative effects of different preferences.

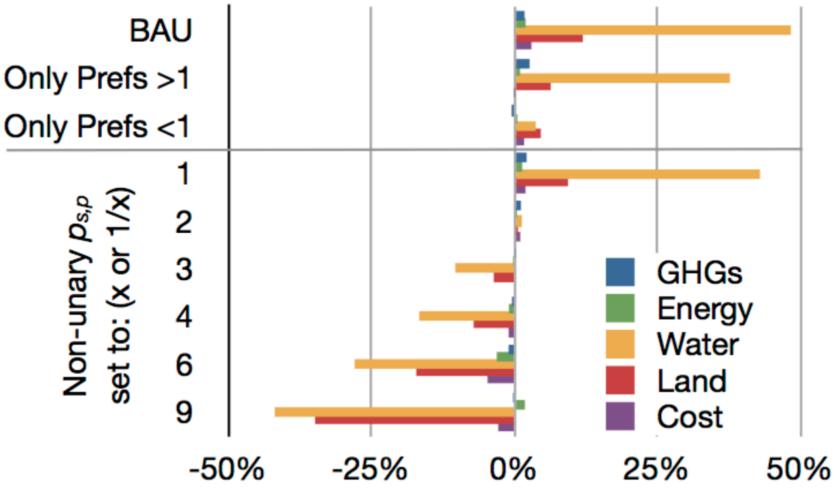

Figure 24: Percent change between cumulative impacts of MSH-PA scenario and variations

All variation scenarios modify policy preference factors, either selecting only amplified sources, only damped sources, or setting all non-unary factors to a specific value (x or 1/x).

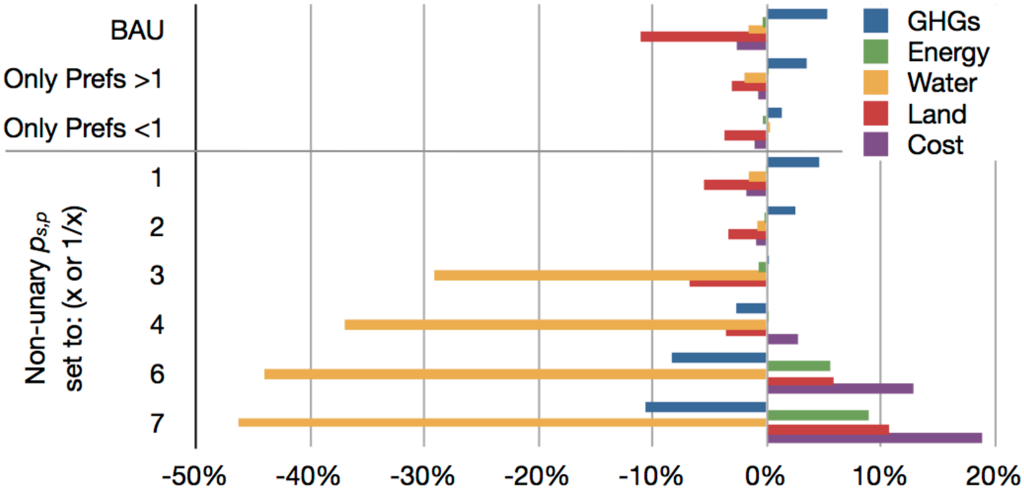

Figure 25: Percent change in cumulative impacts between the REN-PA scenario and variations

All variation scenarios modify policy preference factors, either selecting only amplified sources, only damped sources, or setting all non-unary factors to a specific value (x or 1/x).

The percent changes in cumulative impacts between the MSH scenario and its variations are shown in Figure 24, while the percent changes in cumulative impacts between the REN scenario and its variations are shown in Figure 25. The MSH case shows the 30+% differences in water use in both the BAU and in the case where only positive preferences are used. The case where only negative preferences are used is close to the MSH case results, suggesting that emphasizing NG is insufficient to reduce biodiesel usage by itself, but that de-emphasizing coal, petroleum, and associated biofuels has much larger effects.

Increasing magnification of preference factors reduces biofuels and associated water and land impacts. The remaining three impact categories decrease through a magnification of 6, and then begin to increase. As more NG is used, a limit is reached on reductions in coal-fired power, causing nuclear power and renewables to be reduced in addition to coal *This final aspect suggests that widespread use of the MS might save a small amount of cumulative emissions beyond reductions from retiring coal plants, but replacing nuclear power with NG or ignoring implementation of renewable technologies may eliminate any potential savings.*

Variations from the REN case show a similar dominance by dampening preferences in shifting cumulative impacts away from the BAU case. A focus only on amplifying renewable shifts has less effect if non-renewable sources are not reduced to make space in the source mix. As preferences increase, GHG emissions drop beyond the base REN case, achieving another 5-10% reduction as positive preferences are doubled or tripled. Along with this decrease in GHG emissions, however, is a tradeoff in the form of energy, land, and cost of equal or greater magnitude. Energy usage is primarily in the construction of renewable capacity, and land usage is a byproduct of harvesting less dense energy sources. Cost increases are incurred during construction and may be reduced as technology improves. Mitigating climate change will have a cost, however, but these results suggest that cost increases are tied directly to additional renewable capacity constructed rather than to interplay between sources. This presents a clear technical or political problem rather than a planning problem – how to reduce costs for building additional capacity, rather than finding a minimally impactful set of energy and water sources.

6.2.3 Conclusions

Pennsylvania's energy future and resulting impacts will depend on choices about the use of natural gas from the Marcellus Shale. The results shown here help to quantify what impact those choices can have. All three cases have the same initial drop in GHG emissions as a result of announced coal plant retirements, which is the primary driver in the 7% drop in GHG emissions between 2010 and 2035 in the BAU scenario. While there is currently media attention around potential reductions in GHGs from replacing retiring coal plants with NG plants, the results of the MSH case and basic mathematics suggest that a high preference for NG will not drive continuing reductions in GHG emissions under currently expected national trends. The MSH case shows less than a 2% drop in GHG emissions beyond those already included in the BAU (Figure 17). Further, the retirements seen now should be paired with efforts to plan for transitioning away from NG to avoid a plateau at lower but insufficiently reduced GHG emissions, when considered relative to the physical limits necessary to limit likely global warming to 2ºC [229].

If PA chooses to emphasize renewables, the short-term increase in NG usage appears closer to the much-discussed 'transition fuel' scenario, where NG is utilized while renewables are expanded to replace fossil fuels in general. This scenario is the only one of the three examined that has the potential to be within the definition of sustainable development, but it will require additional capital expenditures and the development of much of PA’s wind and biomass resources. Even with a strong emphasis on renewables and double the reduction in cumulative GHG emissions over the BAU case, the cumulative emissions in the REN scenario show only a 5% drop relative to BAU. The difference between these values is attributable to the gradual increase in low-carbon electricity generation, and the potential reductions are limited by the minimal changes in transportation and heating energy sources. The national trends that all three scenarios are based on are conservative, and a sudden rise in the use of electric cars could replace a larger part of hydrocarbon fuels, or aggressive energy efficiency campaigns could reduce total heating demand. Both of these options would reduce impacts in several categories beyond the changes investigated here, and both options could occur under any of the three scenarios, though they fit with the story of the REN scenario. Achieving sufficient reductions in impacts, regardless of category, will require consideration of more than just electricity.

One unexpectedly important impact of PA’s WEN is the use of biodiesel, which may require large amounts of land either within or outside of the state, and, if external, may generate large water consumption that should be ‘allocated’ to PA consumers and businesses. With PA’s portion of advanced biofuels expected to come from biodiesel, these impacts are important in both short- and long-term planning, and often undiscussed. PA’s WEN is stable and unstressed due to the state’s ample water supplies. The important questions for planners or citizens interested in reducing PA’s contribution to climate change must therefore be in identifying a path for using NG from the MS as a transition fuel rather than a new dependence.

Undiscussed in these scenarios are potential changes in demand. PA has implemented one key pro-active policy, Act 129, which requires a reduction in sales of electricity by 1% and

3% in 2011 and 2014, respectively. In addition to providing rebates for energy efficiency upgrades by homeowners and businesses, this policy has incentivized energy efficiency rebates by electrical companies and driven the adoption of newer technologies.

Transportation energy has yet to show a clear trend. National trends towards lower vehicle-miles traveled may reduce transportation energy usage but are driven by higher fuel prices rather than specific targets. Economic incentives may be sufficient, but progress can be eliminated if prices decrease. Urban planning to allow multi-modal transportation has also received little funding from the state so far, though the two major cities (Pittsburgh and Philadelphia) have pursued initiatives on their own such as the creation of bike lanes. Several studies around PA's rail system and public transportation are ongoing and may result in physical actions.

Programs such as the 2030 District in Pittsburgh are representative of efforts to increase the efficiency of buildings and reduce energy for heating and cooling, both for commercial and residential buildings. Higher fuel costs and/or tighter budgets provide economic incentive to monitor and improve building energy usage. New energy auditing companies have also provided local employment. All of these programs are expected to decrease energy demand over time, directly reducing impacts.

For a given demand pathway, the relative paths of the three scenarios discussed seem likely to hold, providing three plausible if conservative options. As with Brazil, identifying the best approaches for reducing impacts is aided by considering the individual impacts of population change, per-capita consumption, and impacts per unit demand. Reaching physically-sufficient GHG emissions goals will require a combination of efficiency, actual conservation, and shifting sources, and new sources may show impact tradeoffs, with energy and cost on one side and water and land requirements on the other. In the opinion of this work, PA should use the finite resource of the MS as a source of energy and capital to follow a more aggressive version of the REN scenario, such that when the NG supply decreases, PA's energy future is as secure as its plentiful water supplies.

6.3 REPLACING GROUNDWATER IN ARIZONA

6.3.1 Scenarios Examined

Arizona has a similar electricity mix and energy usage as PA, though it is further from the sources of its fossil fuels. The primary resource of concern for planning purposes for AZ is water – both overall consumption and what supplies to use. Currently AZ obtains ~46% of its water from groundwater, at rates that are acknowledged as unsustainable [3, 16, 116]. Its share of the Colorado River, accessible to the center of the state via the Central Arizona Project (CAP), is energy intensive but only partly utilized, providing one avenue for increased or shifted supply. The other primary alternative is to reclaim salty water or municipal sewage for drinking water supply. This approach, while also energy intensive, offers a more expandable alternative. This work examined scenarios related to the question of reducing groundwater consumption, and the overall impacts that such a shift is likely to have.

The base case, again representing a business as usual scenario (BAU), was based on the EIA's AEO, with the percentage of electricity from biomass capped at 5% before natural variation, and oil phased out as an electricity source by 2015. The basic water scenario was taken from a 2012 Bureau of Reclamation study on the Colorado River basin, and provided specific values for total expected demand and a breakdown of Colorado and alternative sources [16]. The base case demand for AZ from that study was used for the BAU-AZ case, and showed a total expected demand of $7.3\text{x}10^9$ m^3 in 2035.

The desalination scenario (DES) replaced half of groundwater demand (16%) in 2035 with desalination, with a linear growth curve for implementation of the technology. The water demand was again based on the BoR study's base case, reflecting a balance of population and per-capita trends. It was assumed that all desalination was used for potable water supply because of the additional cost to desalinate water. No preferences were set for energy sources, although known changes such as new concentrated solar thermal (CST) plants were included.

The third scenario combined the DES scenario with preferences for renewable energy (DES+REN). These preferences were identical to those used for the PA-REN scenario (Section 6.2.1), with natural preferences adjusted to Arizona's conditions [181]. No additional plants or policies were included, and no extra preferences were set for desalination.

6.3.2 Results

Annual impacts in all categories for all three AZ scenarios are shown in Figure 26 as a percentage of 2010 BAU results. Cumulative impacts are compared in Figure 27, and absolute values are available in Table 40, Table 41, and Table 42 in Appendix D. Arizona is expecting an increase in population at twice the national projected rate, and this helps to drive impacts upwards in all categories. In the long term, GHG emissions rise 10% by 2035, energy and land rise 30% and 37% with similar profiles, and water consumption and land occupation rise 60% and 49% with the steepest gains during the latter half of the scenario.

AZ's electricity mix in the BAU case follows the smaller reductions in coal usage inherent in the AEO projections, replacing coal with NG and a signficant amount of solar (12% by 2035). Unlike PA, AZ's solar insolation and available space make concentrating solar thermal a viable option, and a large portion of new capacity was expected to be solar thermal, operating in a similar manner to a low-cf fossil fuel plant. Transportation and heating both show minimal change in sources over time.

Water supplies in AZ use large amounts of infrastructure to move water, and this is reflected in water and wastewater's contribution to overall impacts. Where PA shows a maximum of 6% for both water-related demand classes, AZ shows a maximum of 32% for water consumption, largely from evaporation of the Central Arizona Project. Water-related classes are also responsible for 20% of energy consumption, again due to the CAP. As with PA, demand-side policies and shifts were not incorporated in these scenarios, and water efficiency or conservation measures could offset the high share of impacts from water supplies.

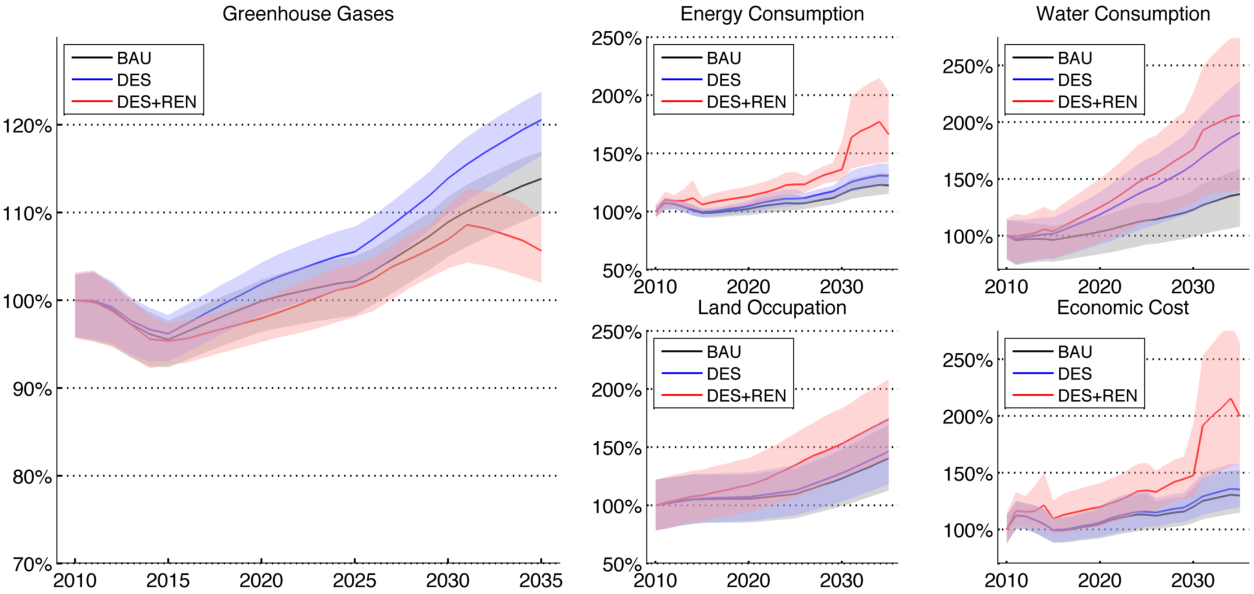

Figure 26: Annual impacts for Arizona scenarios

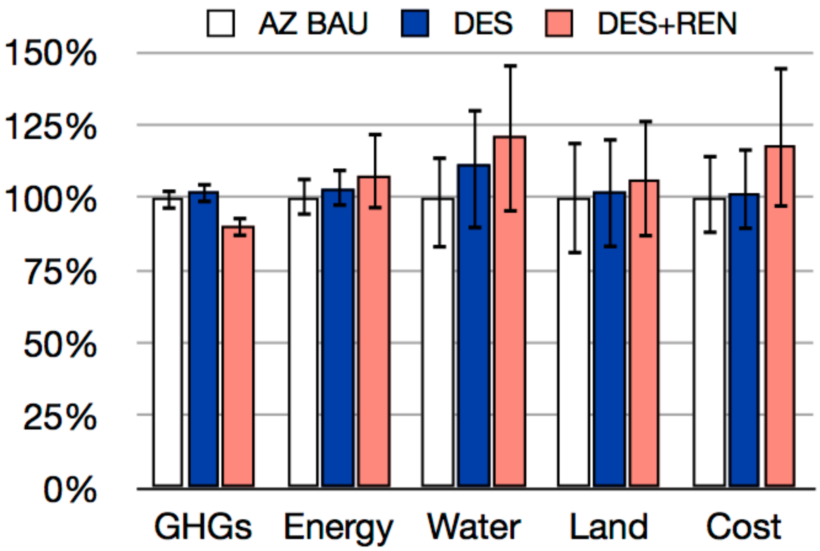

Figure 27: Cumulative impacts of Arizona scenarios

6.3.2.1 Greenhouse Gas Emissions

GHG emissions are shown with physical units in Figure 28. The initial dip in emissions from 2010-2015 is a result of national trends decreasing the use of coal and new planned solar generating capacity becoming available. The increase from 2015-2035 is a result of population increases outweighing a decrease in GHGs/MWh from 345 kg CO_2-eq to 280 kg CO_2-eq. Because of this decrease, GHGs are the slowest growing of the five impact categories, increasing 14% by 2035. Much of this

Desalination adds an additional energy burden even in comparison to importing water through the CAP. This burden translates into additional demand and impacts from electricity, doubling water related GHG emissions, and increasing cumulative GHG emissions by 3% under the electrical source mix of the BAU and DES scenarios. In the DES case, energy-intensive desalination capacity comes into use at the same time that natural gas is expanding as an energy source during the second half of the timeframe. In the DES+REN scenario, the preference away from fossil fuels and towards renewable sources, particularly solar, expands these sources instead of NG during the 2025-2035 timeframe. As a result, cumulative GHG emissions in the DES+REN case drop by 4% relative to the DES case, but are only 1% different from the BAU case. The conservative nature of the AEO's reference case, except in the final five years, means that it provides few opportunities to amplify solar power over fossil fuels. AZ's Renewable Portfolio Standard is thus the driving force behind the increase in renewables, and while sufficient to offset impacts from additional electricity demanded by desalination, it is insufficient to drive a peak and reduction in GHG emissions. If PA's moderate GHG emission reductions were insufficient, AZ's increase in emissions trends in the wrong direction, as even with increasing population, emissions still need to decrease to meet a physically-based goal of 2ºC of average global warming.

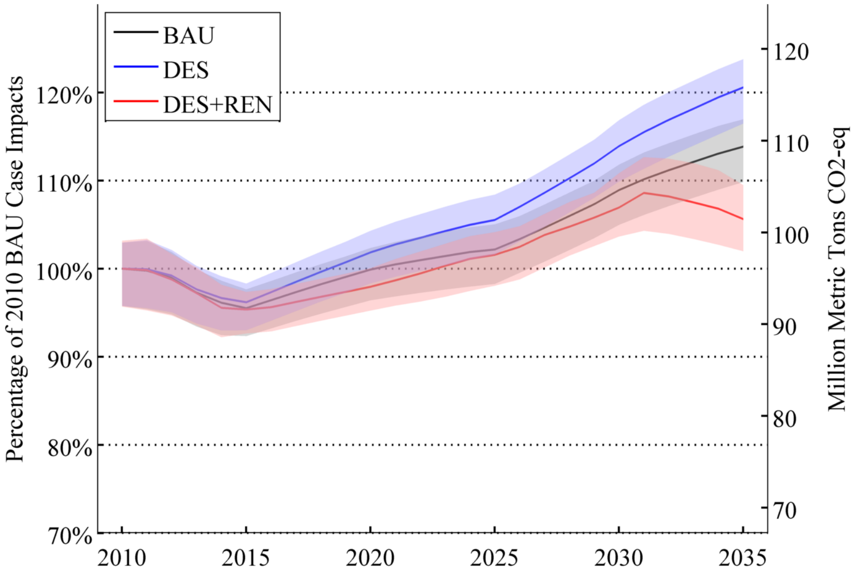

Figure 28: Annual GHG Emissions for AZ Scenarios

6.3.2.2 Energy Consumption & Economic Cost

AZ's energy and water future is trending towards the use of an expensive water source, desalination, and an expensive electricity source, solar power. The term expensive here refers to both economic cost (Figure 30) and energy consumption (Figure 29). The cumulative cost is 2% higher for the DES case than the BAU, but cost per m^3 of freshwater increased by 67% from \$0.27/m^3 in 2010 to \$0.45/m^3 in 2035. Although cumulative cost would change in response to conservation or efficiency, end users would still see an increase in the unit price of water as a result of technological changes if desalination was in use.

The small peaks seen in the first three years in energy consumption and cost are due to construction of new capacity. Energy consumption shows the most variability as periods of constructing solar power capacity cause pulses of impacts, demonstrating the advantages of modeling construction as it occurs rather than levelizing it over the lifetime of equipment. Much of this variation in energy consumption will be in the form of transportation fuels used during construction, and its sudden need does not drive construction of new capacity. Instead, this transportation energy demand would be allocated to the energy and water supply sectors rather than construction in other market sectors.

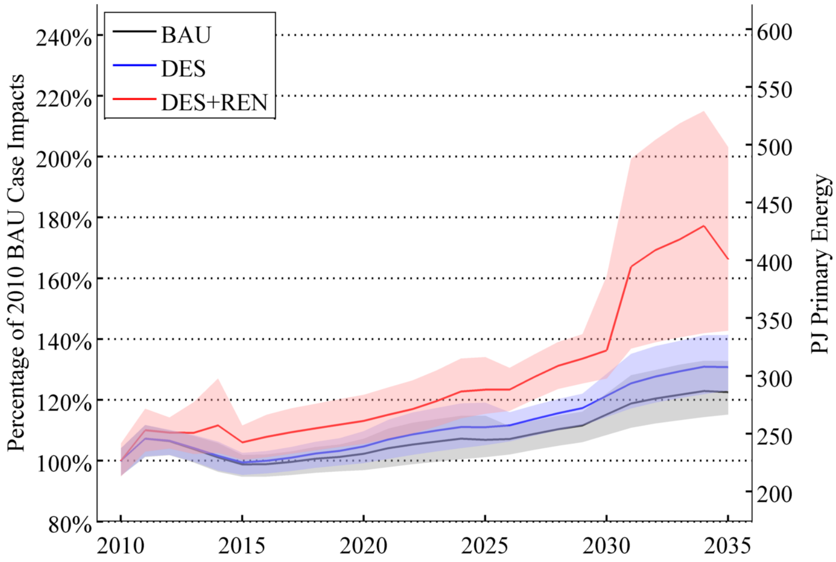

Figure 29: Annual Primary Energy Consumption for AZ Scenarios

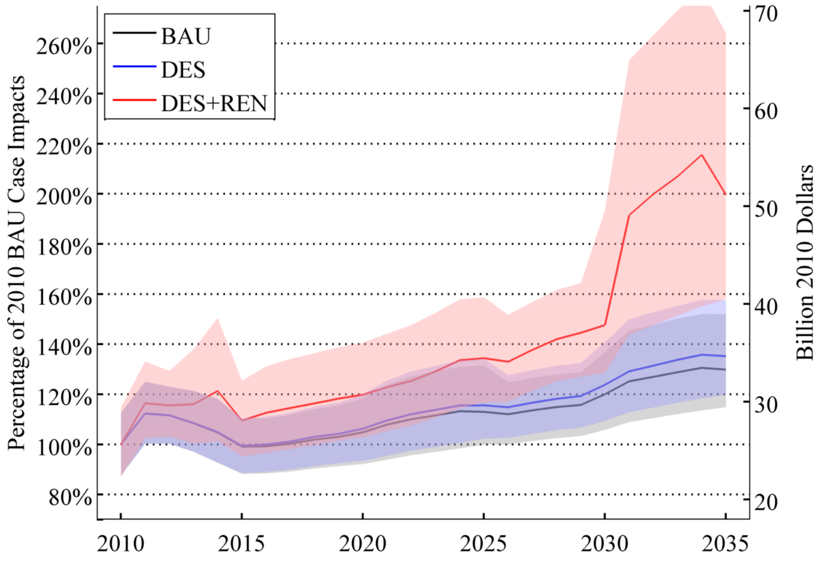

Figure 30: Annual Economic Cost (2010 Dollars) for AZ Scenarios

6.3.2.3 Water Consumption & Land Occupation

Land occupation (Figure 32) shows a slow but steady increase over the course of all scenarios. 75% of the impacts are used for annual production of biofuel feedstocks. Like PA, biofuels may create a significant burden because of AZ transportation demand, an impact that is likely to occur outside of the state. Unlike PA, less change in the usage of biofuels is expected. An increase in the production of algal biodiesel, however, could have very large in-state impacts, attempting to take advantage of high solar insolation but potentially depleting large amounts of water. AZ has a very concentrated population and a non-forested ecosystem, potentially allowing more land to be easily located for land-intensive energy and water options.

Several aspects of the DES and DES+REN scenarios are likely to cause an increase in water consumption (Figure 31). Desalination has higher water consumption as a result of brine production. This water may or may not have been usable for human endeavors before treatment, but is of much lower quality afterwards, unavailable to downstream ecosystems, and considered to be consumed in the REWSS model. In addition, while photovoltaic panels require water during production but minimal water during use, concentrating solar thermal (CST) power plants are thermoelectric and require cooling. In addition to being land intensive, these plants will likely require some source of water to absorb heat. Dry cooling options exist, but decrease plant efficiency, making them unlikely to be used for all new installations. The water consumption of desalination and CST plants combines in the DES+REN case, increasing water consumption by >200% over 2010, as well as expanding uncertainty because of variability in technological options.

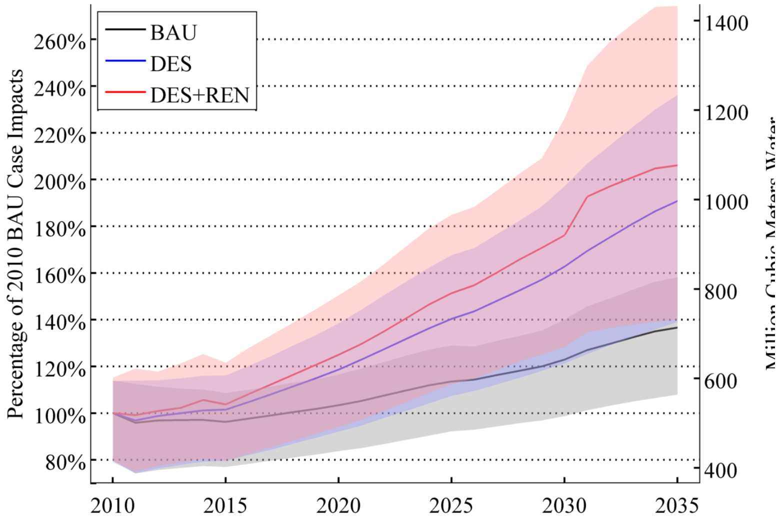

Figure 31: Annual Water Consumption for AZ Scenarios

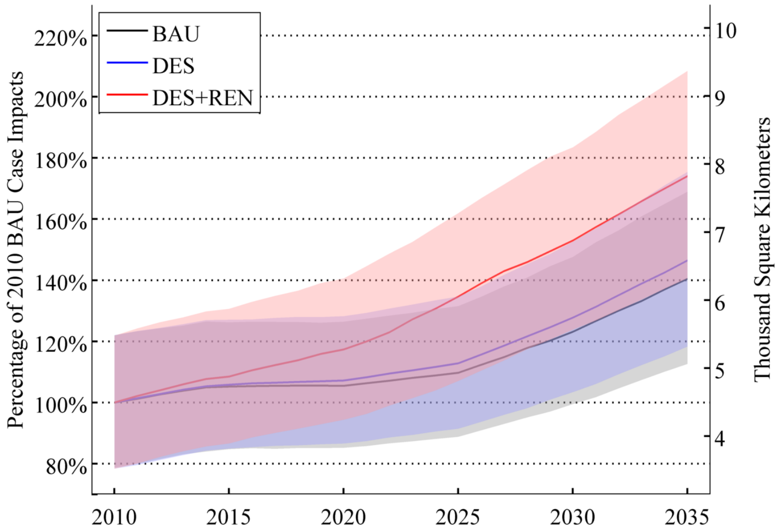

Figure 32: Annual Land Occupation for AZ Scenarios

Table 15: Source mixes for AZ scenarios

	AZ Start	*AZ BAU*	*AZ DES*	*AZ REN+DES*
Source	2010	2035		
Coal	35.5%	21.1%	21.1%	18.9%
NG	31.0%	37.5%	37.9%	24.4%
Oil	0.1%	0.0%	0.0%	0.0%
Nuclear	27.4%	18.0%	18.0%	26.3%
Hydro	5.9%	4.5%	4.4%	8.1%
Biomass	0.1%	5.0%	4.8%	4.9%
Wind	0.0%	1.0%	1.0%	1.6%
Solar	0.1%	12.7%	12.5%	15.2%
Geothermal	0.0%	0.3%	0.2%	0.5%
Petroleum	93.5%	90.5%	90.5%	91.3%
EtOH	6.0%	7.5%	7.5%	7.7%
Biodiesel	0.1%	0.2%	0.2%	0.1%
CNG	0.5%	1.8%	1.8%	0.6%
Hydrogen	0.0%	0.0%	0.0%	0.0%
Electric	0.0%	0.0%	0.0%	0.2%
Coal	5.9%	7.4%	7.4%	6.9%
NG	48.9%	49.7%	49.8%	51.7%
Petroleum	39.8%	37.3%	37.3%	35.2%
Biomass	5.5%	5.5%	5.4%	6.1%
Water-Surface	11.7%	12.3%	12.9%	12.8%
Water-Ground	48.2%	37.5%	18.5%	18.6%
Water-Import	40.0%	50.1%	52.5%	52.5%
Water-Desal	0.1%	0.1%	16.1%	16.1%
WW-Trickling	0.0%	0.0%	0.0%	0.0%
WW-Aerated	11.2%	8.7%	8.7%	8.7%
WW-Adv-NoDeN	28.1%	31.5%	31.5%	31.5%
WW-Adv-DeN	60.7%	59.8%	59.8%	59.8%

6.3.2.4 Water-Energy Connections

Arizona's WEN is strongly connected and likely to become moreso going forward. The primary example is the CAP, which uses 2-3% of the state's electrical demand to provide water to Phoenix and Tucson for treatment. Overall electricity use for water (LfW) from model results was 7.4%, with EfW at 3.5%. On the other side of the WEN, the lack of plentiful surface water requires thermoelectric power plants to almost entirely use closed-loop cooling, helping place WfE at 5.3%. Arizona uses less biofuels than PA, decreasing the imported water consumption associated with such fuels.

Future changes will increase these interconnections. Under the base case, EfW and LfW both increase by ~1%. While PA sees water consumption increasing for its state footprint, but actual impacts occuring elsewhere, AZ sees steep increases in the interconnection – and resulting stress – on both the WfE and EfW sections of its water-energy nexus. Alternatives are unlikely to alleviate this stress. Desalination increases LfW to 9.7%, while wider use of solar power increases WfE to 5.9%. These small changes represent a large amount of energy and water, particularly with increasing demand.

It is important to note that while AZ's WEN may see increasing stress, this stress does not necessarily translate into infeasibility as concerns sustainable development. While the two resources may be more connected, it is likely possible to find sufficient sustainable resources to meet demand. The concern is that net energy and net water available for regular purposes will be less available. This limit, however, is socioeconomic or political, rather than a physical sustainability barrier. Desalination may be a valid option for improving the sustainability of water supplies, as long as it is implemented with the knowledge that less energy will be available for other uses.

6.3.2.5 Sensitivity of Results

AZ is part of the WECC-Southwest electricity grid, and when AEO trends for this region are used in place of the national trends for the BAU scenario, the cumulative GHG emissions are 6% higher. However, there is a large discontinuity in NG and coal usage in the first five years of the data, after which the national and WECC-SW trends show near-identical results. This discontinuity is difficult to assess, but with AZ's status of exporting ~25% of electricity generation, the in-state results are likely to be a more accurate representation of true impacts.

Comparing WECC-SW and AZ emissions intensities, there is a 0.2% difference, minimizing any potential difference in results from using a different source mix.

As with PA's scenarios, the robustness of the results of AZ's scenarios was tested by varying user-input preference factors as a measure of sensitivity. Alternatives were run using only positive preferences ($p_{s,n}>1$), only negative preferences ($p_{s,n}<1$), and varying both sets of preferences simultaneously from 1-9 or 1-0.11. For the DES case where no preference factors were initially set, the preference for desalination alone was modified. Results are reported as percent difference between cumulative values of the basic scenario and the alternative. Results for alternatives to the DES scenario are shown in Figure 33, and results for the DES+REN scenario are shown in Figure 34.

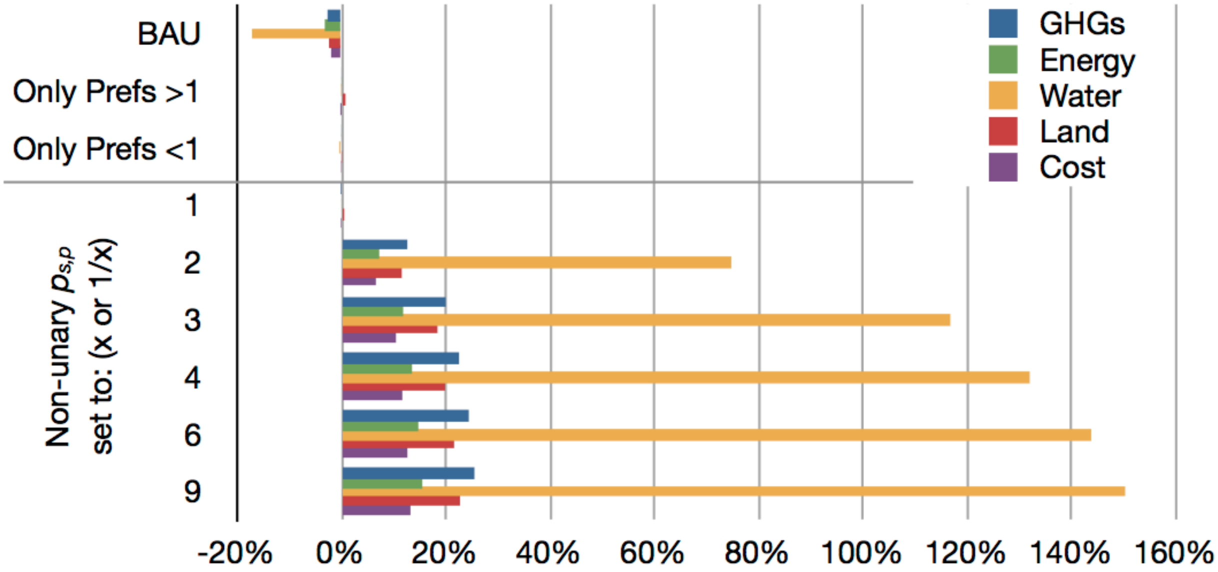

Figure 33: Percent change in cumulative results between the AZ-DES scenario and variations

All variation scenarios modify policy preference factors, either selecting only amplified sources, only damped sources, or setting all non-unary factors to a specific value (x or 1/x).

For both DES and DES+REN scenarios, increasing use of desalination dominates the variations through increased water usage. The percentage of water from desalination is extremely sensitive to preference factor, which is set to 1 in the basic DES and DES+REN scenarios, but varied up to 9 to examine sensitivity. As desalination's fraction of the source mix reaches 100%, water consumption increases by a factor of two. It is unlikely, however, that preference factors are as appropriate for water sources as for energy sources because of the differences in the two industries supplying them. While energy preference factors can be interpreted as subsidies or taxes and fines, water supplies tend to be subsidized by governments directly rather than incentivizing private industry to one technology or another.

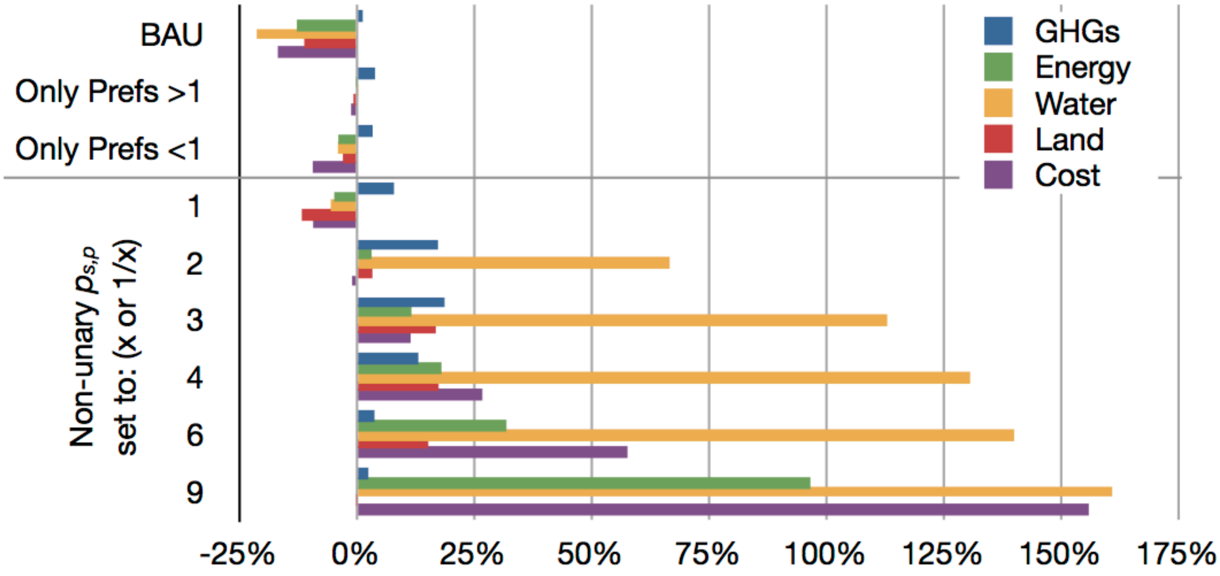

Figure 34: Percent change in cumulative results between the AZ DES+REN scenario and variations

All variation scenarios modify policy preference factors, either selecting only amplified sources, only damped sources, or setting all non-unary factors to a specific value (x or 1/x).

The difference between the two scenarios' variations is visible in GHGs. The DES case shows an increase in GHG emissions as more desalination is used, as part of a feedback in demand for electricity. When renewables are included, GHG emissions rise initially, but are cancelled out at high levels as very high penetration of desalination technologies is matched by very high penetration of solar power (both of which are unrealistic). In the variations that use only positive or negative preferences, the increase in GHG emissions in both cases is indicative of a need to jointly remove fossil-fuel infrastructure and prioritize renewable technologies to replace it.

6.3.3 Conclusions

Arizona has a similar set of energy source mixes as PA in 2010, but its future impacts and decisions will likely concentrate on where water will come from and the sustainability of future water. Under the BAU scenario, AZ shows a steady increase in GHG emissions and other impacts, the result of an increasing population and a coal dependent mix, with less replacement by NG. Where PA's GHG emissions reductions are insufficient to meet physical limits to limit warming, AZ's emissions are still increasing, and need to level off first before declining – an added challenge. The only scenario where this reduction seems feasibile is in the DES+REN case, where large tradeoffs to energy consumption and costs may be incurred. In addition, AZ's WEN is significantly more relevant than PA's, with a slightly higher percentage of water used for closed-loop cooling but twice the percentage of electricity and energy used for supplying water. The main driver is the use of the CAP and, to a lesser degree, increasingly energy-intensive groundwater wells. Attempts to reduce GHG emisisons will be more difficult harder because of physical limits on energy requirements for lifting water. Instead, the additional energy needed to supply water will likely make conservation or efficiency necessary.

One option under consideration for reducing groundwater and dependence on CO river water is to reclaim water via desalination. Shifting half of groundwater supply to desalination increases cumulative impacts in all categories, an expected result. However, efforts to use renewable energy sources to offset increased GHG emissions show a tradeoff with the impacts and costs of shifting infrastructure. Solar power, in particular, has a high and uncertain energy consumption during construction, higher land usage than fossil fuels, and high cost with current technology. Water consumption increases further under the DES+REN scenario, from both construction impacts and cooling demand for concentrated solar thermal plants.

If AZ wants to reduce its environmental impacts, whether for environmental or economic reasons, conservation will likely need to be part of the plan, so that energy or water intensive new sources of water and energy have spare resources to utilize. Rising populations make reductions in impacts more difficult, but the DES+REN case demonstrates that reductions, at least to GHG emissions, are achievable, if only with tradeoffs. Several demand-side efforts are underway, and may shift AZ's water or energy demand in any one of these or other supply scenarios. Central among these is AZ's Energy Efficiency Standards, which requires cumulative electricity savings of 22% and natual gas savings of 6% by 2020, one of the most ambitious targets in the country. This Standard is in addition to an existing RPS that can drive basic implementation of renewable electricity generation. As with PA, less concerted policy effort has gone into reducing transportation energy usage, although federal fuel efficiency standards will contribute significant gains over the course of the coming decades.

For water efficiency, no comprehensive policy is currently in place. A significant amount of educational programs are available, as well as efforts by major metropolitan areas to improve efficiency, such as Phoenix's receipt of the EPA's WaterSense award. Because water is more limited and energy intensive, it is also more expensive, providing economic incentive to conserve or find more efficiency appliances. State and municipal water plans, however, have focused more on how to find supplies to meet growing demand rather than identifying ways to curb demand [116, 117]. This work has taken a similar approach, with the caveat that testing reduced demand scenarios is a straightforward task using REWSS. The combination of educational programs, efficient appliances, and economic incentives will likely reduce demand, though the lack of a clear goal may reduce the overall effectiveness of these efforts.

AZ is a region that will be able to easily see stresses and physical limits on its WEN in the coming decades. Sustainability is important, if also likely feasible, in both energy and water, though possibly with less net energy and water. The availability of high solar insolation provides a more stable long-term position in many ways – it is easier to use energy to move or treat water than to use water to create or capture energy, although economic costs may be a barrier to either. AZ's unsustainable groundwater will remain a key question for planners, and desalination may provide a partial solution, in the sense that it alleviates water supply issues while increasing stress in many other areas. Whether the end result is more or less sustainable will be determined by those other areas, particularly the electricity supply. AZ is also facing a growing population and rising resource demand at a time when carbon emissions should be peaking and falling, creating an extra challenge, though one without as many local consequences. AZ should, in the opinion of this work, pursue desalination options while simultaneously aiming to install as much photovoltaic capacity as possible, and institute clear goals for water efficiency.

7.0 CONCLUSIONS

Three major trends have separately appeared in energy and water planning in recent years, all of which are connected to this work. First are the increasing impacts of climate change – more intense droughts, stronger storms, and warmer and higher oceans. Although only indirectly impacting how energy is supplied – though biomass is harder to produce in droughts and power plants are less efficient with warmer water – climate change is a result of the current fossil fuel-heavy mix of sources that is currently in use. An effective response to climate change will require using less of these fossil fuels, and sustainable development requires eliminating them.

The second trend is the shrinking availability of water in much of the western half of the U.S. and many other regions around the globe, whether through climate change related precipitation changes or the depletion of fossil aquifers. Because water is dense and difficult to move, regional limitations are an impediment to regional sustainability and expensive – in both dollars and MJ – to mitigate.

The final trend is the recent creation of methods for economically recovering natural gas from shale formations, significantly increasing available domestic NG resources and raising the question of how these resources will be used. As fossil fuels, those interested in sustainability urge avoidance or caution in their use, but the NG also represents a low-cost source for supplying energy to mitigate other problems such as pumping or desalinating water.

All three of these trends are intertwined, and which one is dominant is dependent on the region. However, all three are driving the creation of new policies and resource planning efforts that will have socio-political impacts at the macroscale. This includes state AEPs and RPSs, state water plans, and, in states with shale gas reserves, new regulations to attempt to mitigate impacts and manage the development of this energy source. Because of the scale of these efforts, tools that take a wide but still regional approach are required. Current research efforts have been fragmented, investigating particular sources or regions, with little ability to assess a swath of possible options to find key factors for necessary changes. This dissertation focuses on collating information and creating a tool to help planners supply water and energy while mitigating rather than exacerbating environmental problems and resources scarcity. Tying together the impacts of shale gas with an assessment of these trends for three very different regions, the results of this work have broad implications in a complex but critical space. This final chapter steps through these results, suggests future work using the overarching REWSS model, and connects these three trends with the results to discuss the future of sustainability and the water-energy nexus.

7.1 THE MARCELLUS SHALE

Shale gas is termed unconventional because of the need to use new methods such as horizontal drillling and hydraulic fracturing in order to economically extract the gas. Our results, which correspond with a growing consensus around basic environmental impacts, suggest that the GHG emissions, energy consumption, and water consumption over the life-cycle of shale gas are quite similar to conventional NG. One of the real differences between shale gas, particularly the MS, and conventional NG is that its low permeability and absence of a connected reservoir requires many well pads to extract all of the technically recoverable reserves. Because the MS lies underneath a populated and developed, if often rural, region, these well pads may have larger societal impacts. In addition, there are still questions around fugitive methane emissions and the public health risks of spills and condensate tanks.

For larger questions of energy policy, the hope is that the current information is sufficient to inform next steps. That information, amplified by the work discussed in Chapter 3, suggests that although aggregate GHG emissions may not be drastically higher, depletion rates and a plethora of less-productive threaten both ultimate recovery rates for the formation and EROI of shale gas in general. In terms of climate change, a 40% reduction in GHG emissions relative to coal is woefully insufficient to meet the reductions necessary for effective mitigation [138, 229]. For political and economic reasons, however, without a clear alternative for wealth generation in rural PA and energy generation throughout the country, it is unlikely that society will easily transition away from NG, threatening climate goals at every level. In the sense that this energy source will be likely be with us for a long time, having more information collected on it is critical, and being able to provide an estimate of EROI and identify the large uncertaintities in water consumption and certain production processes represents a valuable contribution.

7.2 REGIONAL CONSIDERATIONS

7.2.1 Brazil

Brazil, unlike PA and AZ, is still developing. Because of this, energy consumption and aggregate GHG emissions are expected to rise rather than fall in the coming decades, an effect accounted for in global planning and allocation. Under the electricity scenarios studied, however, Brazil will find it more difficult to meet even generous carbon emissions targets because of a rise in the usage of NG and coal-fired electricity. The widespread implementation of large dams in the Amazon basin has the potential to further increase GHG emissions, though there is considerable uncertainty about the net values of these emissions.

Brazil's path forward on electricity is likely to be dominated by development goals rather than adherence to environmental priorities, and though increased efficiencies can offset some relief, careful design of new hydropower plants or large-scale expansion of wind energy will be necessary for effectively supplying increased electrical demand without sacrificing Brazil's low-per-capita electricity impacts. The state of Brazil's WEN is not a simple answer – like the US, regional considerations are required, and further research using the full REWSS model could be beneficial, particularly in incorporating impacts or reductions thereof from sugarcane ethanol usage, and potential shifts in impacts as wastewater treatment infrastructure is created.

7.2.2 Pennsylvania

Pennsylvania has been the location for development of many energy technologies, most recently shale gas from the Marcellus Shale. While the MS has been touted as the solution to American energy needs, realistic estimates of resource availability, depletion rates, and societal questions of what the physical landscape would look like under full production may hamper the MS's long term potential. In addition, although retiring coal plants and a shift to NG for electricity are producing a sudden drop in GHG emissions for both the state and US, without explicit and concerted effort, PA runs the risk of levelling out at a lower emissions rate, but one that is far too high for effective mitigation of climate change. The results of the BAU and MSH scenarios

(Section 6.2) show a need to prioritize renewables, even as emissions decrease from retirements, if physical rather than political GHG emissions goals are to be met.

The biggest stress on PA's WEN may come from biofuels, which may also drive a conflict over land use between biofuels, biomass for heating, and possibly shale gas drilling. With its plentiful water supplies, the results of this work show a lower risk of large tradeoffs from widespread use of renewables, making a sustainable WEN a reasonable, if difficult, target for the current generation of planners and builders.

7.2.3 Arizona

AZ is a state dependent on external non-renewable fuels for energy and importing a significant fraction of its water as a junior user in the Colorado watershed, and results show increasing connections between energy and water, along with their associated impacts. From a purely environmental perspective, the best option for AZ would be to slow population growth and focus on efficient use of water and energy. Efforts to increase sustainability by providing water through desalination are a valient goal, but require additional energy that will, under current pathways, increase impacts across the board, including removing water from downstream ecosystems that tolerate higher levels of dissolved solids. The conclusion of this researcher after spending a year studying Arizona is that Phoenix should not exist in its current form. The local ecosystems, regardless of their high potential for solar power or heating, do not have the carrying capacity to supply energy and water to a large population without large and increasing parasitic impacts between energy and water. The WEN is a serious concern for AZ, and one that is unlikely to be solved by shifting sources – efficiency, conservation, and a lower population are the only long-term approaches.

7.2.4 Energy and Water in General

It is clear from collecting the information for this work that energy and water are tracked and regarded in very different ways by their respective industries and government agencies. Energy infrastructure and resources are metered on a monthly or even weekly basis, with information on existing capacity easily available; similar information for water infrastructure is scarce or non-existant. Water and wastewater systems are physically separated; energy systems are connected grids or markets with significant interconnections. Finally, energy is primarily a private sector activity, while water and wastewater are primarily the space of public utilities. Regardless of dominant explanations for these differences, sharing some tracking protocols between the EIA and the EPA, BoR, or USGS would be highly advantageous to better research on the WEN – as would sufficient digital monitoring to permit the publication of the USGS' 'Water Use in the United States' report more than once every five years with a three year delay. In an age where water is as important and managed as energy, its elemental nature should not prevent us from monitoring it at the same level. The same argument applies to environmental impacts, where energy technologies have seen far more academic work than water technologies. This divide is starting to shift, but still requires standardization as to metrics and studies of basic technologies.

Beyond moving towards similar monitoring and data collection processes, several states are beginning to consider the water-energy nexus as part of public policy, which is a welcome shift. PA is unlikely to embrace this approach unless a much stronger desire for more advanced water and wastewater treatment appears, as the water-energy connections in PA are weaker than average. For AZ, however, both water use for energy and energy use for water represent important aspects of ongoing policy discussions around issues like the CAP. Outside of these case studies, there has been a rise in WEN-related reports [31, 95, 127], which are hopefully the vanguard of a more holistic approach to resource planning.

7.3 FUTURE WORK

The REWSS model, built on a basic LCA of an emerging technology and existing data, puts energy and water supplies into the same systemic framework and approach to infrastructure. With the model in Python, the code is usable by any computer, but a visual interface would be valuable for a widespread release. Maintenance of the model would include updating and appending supply sources and modes as more information becomes available. This is particularly true for water-related classes. Automation of regional data collection through the use of increasingly available government databases would increase the easily available regions.

There are several possible improvements to the modeling approaches, mostly around expanding included impact categories or refining system boundaries and included classes. Many of these could be the subject of future research. Key immprovements are as follows:

1. Water quality is a key impact that is not included in any form. For states that cool power plants with open-loop cooling, or states with significant amounts of fertilizer runoff or salts, simply calculating water consumption for energy is insufficient. In addition, energy will often be used to remove pollutants, adding a further reason to investigate including water quality metrics. No single metric has emerged in LCA as a measure of water quality – this researcher suggests that a measure of energy required to bring water to a defined standard of quality be used – and this lack requires either additional data collection for multiple impact

categories or patience while the scientific community standardizes. A second issue is that water quality is less additive over multiple watersheds, making it more difficult to place within the scope of this work.

2. Transportation is currently implemented as the total energy consumption, but this obscures both easy measures of vehicle efficiency and different types of transportation. A better approach, albeit one with additional difficult data collection requirements at the regional level, would be to split transportation into personal mobility (person-miles) and freight transport (ton-miles). Treating transportaiton as two separate classes would allow for more appropriate technology pathways, and the use of increasing efficiencies rather than decreasing capacity factor for tracking effectiveness.
3. More explicit accounting for energy or water usage on the demand side would provide information that may be beyond the intended use of this model, but be of use to users. A key example is the use of energy for heating water in buildings. These two aspects are technically present in current calculations – some fraction of water demand will be heated, and some fraction of heat demanded is for water – but establishing regional parameters for these connections, while data-intensive, would add key links to discussing the regional WEN.
4. Demand-side changes were briefly discussed for all three case studies, but not explicitly modeled. REWSS can easily consider a scenario with alternate demand pathways, but is also built to allow demand-side policies to be modeled. Future work in this area is needed to improve the accuracy of connections between

demand, capacity changes, and the use of certain sources, as well as to expand the options available for modeling demand-side changes.

5. The model is currently dominated by a linear framework that responds to static scenarios, but a key set of important planning questions involves the best path or the minimum tradeoffs – say, the lowest GHG emissions possible while increasing cost by <10%, or lowest water consumption while meeting GHG emission goals. These questions could be investigated by pairing the median, rather than MCA-enabled, REWSS model with an optimization algorithm. Once an optimal path has been determined, the standard MCA-enabled model can be run to assess uncertainty.
6. Regional life-cycle impacts are important, but final results would be improved by inclusion of a built-in assessment of feasibility for the region in question. This feasibility would necessarily include available regional precipitation, renewable energy potential, and changes in non-renewable resource stocks. The primary barrier to inclusion is again data availability and the highly regional nature of feasibility.
7. From a technical perspective, Python is a versatile and reasonably platform-independent language, but long-term storage of LCA and regional data should be done using a database rather than in code. Ideally, the database would be publicly visible, with the ability for other researchers to submit edits, and linked with a web-based interface for the REWSS model – another property doable with Python. The would make the information more accessible and help in updating LCA data as new options for various sources become available or are better

examined. This approach would also make the addition of new options or sources simpler for end users.

It is the belief of this researcher that the work presented in this dissertation provides new information on a key emerging energy source, a functioning combining many data sets and topics into a holistic calculation, and new insights into the future impacts for the three regions examined. The central REWSS model is made available for other users to glean insights into their own regions, with expansion upon its basic approach encouraged to highlight new sources or interconnections between the WEN. There is much that can be learned from combining region, life-cycle impacts, water, energy, and scenarios, and this tool can be a core part of many future projects. There are far too many accessible questions to investigate in the course of a single degree, and future readers are encouraged to make use of REWSS for their own purposes.

7.4 FINAL NOTES: WHEREFORE THE SUSTAINABLE WEN?

Society, particularly US society, is a long way from a comprehensive awareness of either the water-energy nexus or the implications of sustainability, let alone their combination. In the long run, however, it is the sustainability of our interdependent water and energy supplies that will determine the carrying capacity of regions – whether in Arizona, Pennsylvania, or Brazil. The use of fossil groundwater in Arizona is just as unsustainable a source as coal in Pennsylvania, with the added problem being more difficult to replace. Alternatively, while Pennsylvania has more than ample water resources, its sustainable energy availability will likely be determined by willingness to invest in interstate power lines for wind energy, local solar (everywhere, always), and increasing building efficiency to allow limited biomass feedstocks to be sufficient for heating. Implicit in both of these scenarios is a need to conserve resources to avoid the need to find new ones. An additional debate around sustainability is the self-sufficiency of regions and the related resilience of different options. While society may be willing to devote resources to transporting water to Phoenix or wind electricity to Pittsburgh, both approaches demand long-term up-keep of infrastructure that must also be considered during planning.

There is no single vision of a sustainable world – it is a topic with many correct answers, bounded by straightforward yet difficult-to-implement definitions such as those provided in Section 1.2. In any sustainable world or path towards one, however, identifying connections between energy and water is only one key step, and a redefinition of the WEN to include the sustainability of its components is critical for planners both today and tomorrow. We cannot meet the challenges of today without both a vision of tomorrow and a firmly practical definition of success in getting there, and while a world with a sustainable WEN may not be sufficient, it is the linchpin of physical infrastructure. This work, and future derivatives, have a role to play in helping to plan both the path and the end result of a sustainable WEN.

APPENDIX A

SUPPORTING INFORMATION FOR THE STUDY ‘LIFE-CYCLE ENVIRONMENTAL IMPACTS OF NATURAL GAS FROM THE MARCELLUS SHALE’

A.1 SOURCE DATA AND BASIC RESULTS

Table 16: Distributions Used for System Parameters

			2007-2010			*2011-2012*		
Parameter	***Source***	***Dist. Type***	***Dist. Param. 1***	***Dist. Param. 2***	***Dist Param. 3***	***Dist. Param. 1***	***Dist. Param. 2***	***Dist Param. 3***
Construction Time (Days)	Data table responses	Triangular	35	30	60	33	30	60
Drilling Time (Days)	Data table responses	Triangular	25	16	34	23	13	34
Diesel Usage (gal/day)	Operator Conversations	Point Estimate	2,000			2,000		
Completion Stages (#)	Data table responses	Triangular	9	5	20	14	8	23
Pad Area (sf)	Data table responses	Triangular	2.0E+05	1.1E+05	2.0E+05	8.3E+04	8.3E+04	1.6E+05
Road Area (sf)	Data table responses	Triangular	4.0E+04	1.5E+04	1.2E+05	2.3E+04	7.0E+03	1.4E+05
Depth (ft)	Data table responses	Triangular	1.3	1.3	1.7	1.7	1.0	2.3
Conductor Casing (ft)	Operator Conversations	Point Estimate	60			60		
Aquifer Casing (ft)	Operator Conversations	Triangular	550	500	600	550	500	600
Coal Seam Casing (ft)	Operator Conversations	Triangular	2,500	2,000	6,000	2,500	2,000	6,000
Total Borehole Depth (ft)	Data table responses	Triangular	11,000	6,000	13,000	12,000	9,000	14,000

Table 16 (Continued)

Total Vertical Depth (ft)	Data table responses	Triangular	7,100	4,700	9,600	7,300	4,700	9,905
Lateral Length	Data table responses	Triangular	2,600	1,500	5,100	4,200	2,500	7,150
Sand Used (lb)	FracFocus Reports [1]	Triangular	5.0E+06	4.6E+06	5.1E+06	5.0E+06	4.6E+06	5.1E+06
Breakthrough Gas Rate (Mcf/day)	Operator Conversations	Triangular	800	200	3,000	1,000	200	3,000
% Vented	Data table responses	Binomial	20%			5%		
% Flared	Data table responses	Binomial	75%			63%		
Freeflow Time (hrs)	Data table responses	Uniform	1.0	48		1.0	24	
Solid Waste Production (tons)	PA DEP Reports [2]	Lognormal	10.6	1.0		10.6	1.0	
Water Used (Bbls)	FracFocus Reports [1]	Normal	1.1E+05	3.9E+04		1.1E+05	3.4E+04	
% Pads with Water Pipeline	Operator Conversations	Binomial	30%			70%		
% Makeup Water from Recycling	Data table responses	Triangular	5%	0%	10%	12%	0%	21%
% Water Returned as Flowback	Data table responses	Triangular	25%	10%	40%	20%	5%	35%
Trucking Distance	Operator Conversations	Triangular	60	30	150	60	30	150
Train Distance	Operator Conversations	Triangular	1,000	500	1,500	500	100	1,500

Table 17: Database Processes Used and Associated Materials

Material	*Database*	*Process Name*
Diesel	ecoinvent 2.1	Diesel, burned in diesel-electric generating set/GLO S
Plastic Liner	ELCD	Polypropylene resin, at plant/RNA
Gravel	ecoinvent 2.1	Gravel, crushed, at mine/CH S
Cement	US LCI	Portland cement, at plant/US
Casing Steel	ecoinvent 2.1	Steel, low-alloyed, at plant/RER S
Leaked Gas	ecoinvent 2.1	Leakage production natural gas NL S
Flared Gas	ecoinvent 2.1	Natural gas, sweet, burned in production flare/MJ/GLO S
Sand	ecoinvent 2.1	Sand, at mine/CH S
Trucking	ETH-ESU	Truck 40t ETH S
Train	US LCI	Transport, train, diesel powered/US
Compression Set	ecoinvent 2.1	Natural gas equipment (cuft)

Table 18: Impacts per MJ for 2011 wells using stochastic material distributions

Impact	*Value*	*Well Development*				*Midstream Transport*	*Liquids Removal*	*Pipeline Transport*	*Combustion*
		07-'10		*11-'12*					
		Mean	*Median*	*Mean*	*Median*				
Global Warming Potential ($g\ CO_2$-eq/MJ)	Value	0.73	0.71	0.38	0.37	5.70	0.61	4.00	51.00
	Value as % of total	1.2%	1.1%	0.6%	0.6%	9%	1%	6%	83%
	90% CI - Low	0.33		0.17		2.30	0.51	2.60	
	90% CI - High	50.79		17.49		10.10	0.71	5.00	
Primary Energy Consumption (MJ/MJ)	Value	0.0060	0.0060	0.0038	0.0038	0	0.037	0.035	0.00
	Value as % of total	7.7%	7.7%	5.0%	5.0%	0%	49%	46%	0%
	90% CI - Low	0.023		0.015			0.031	0.033	
	90% CI - High	0.53		0.20			0.043	0.038	
Water Consumption (L/MJ)	Value	0.0035	0.0031	0.0023	0.0021	0	0	0	0.19
	Value as % of total	1.8%	1.6%	1.2%	1.1%	0%	0%	0%	95%
	90% CI - Low	0.0022		0.001					0.13
	90% CI - High	0.14		0.02					0.40

A.2 LIFETIME WELL PRODUCTION ESTIMATES

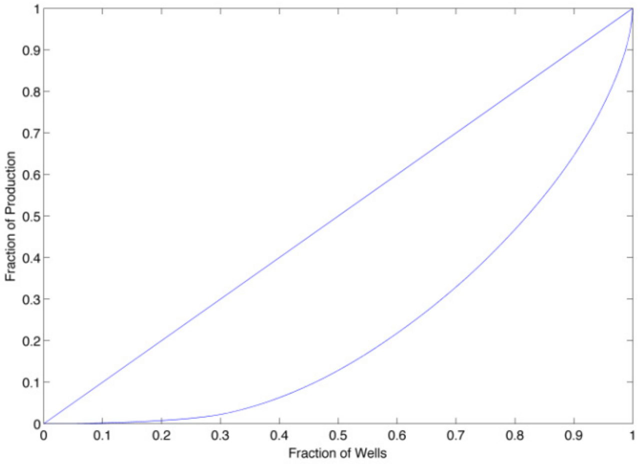

Figure 35: Distribution of wells and production for wells started in 2008-2010

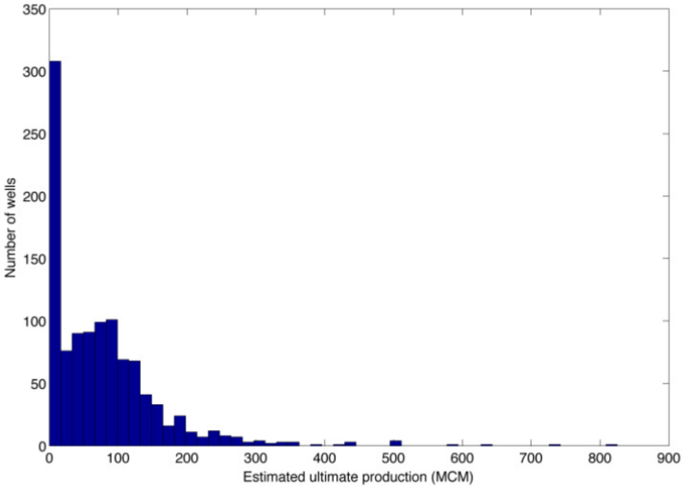

Figure 36: Estimated ultimate recovery for PA Marcellus wells started in 2008-2010

APPENDIX B

REWSS MODEL SUPPORTING DATA

B.1 BASIC STRUCTURE AND INPUT DATA

Table 19: Built-in Sources for the REWSS Model

Source (flag)	*Class*	*Variability*	*Resource Options*	*Capacity Options*	*Operations Options*
Coal (0)	Electricity	Dispatchable	Underground Surface	Steam Turbine IGCC	Closed-loop cooling Open-loop cooling
Natural Gas (1)	Electricity	Dispatchable, Default	Conventional, Shale, LNG	Steam turbine, NGCC	Closed-loop cooling, Open-loop cooling
Petroleum (2)	Electricity	Dispatchable	Conventional	Steam turbine	Closed-loop cooling, Open-loop cooling
Nuclear (3)	Electricity	Dispatchable	Centrifuge, Diffusion	Nuclear Reactor	Closed-loop cooling, Open-loop cooling
Hydropower (4)	Electricity	Annual variation	N/A	Temperate, Tropical (BR)	Temperate, Tropical (BR)
Biomass (5)	Electricity	Dispatchable	Woody biomass	Steam turbine	Closed-loop cooling
Wind (6)	Electricity	Variable	N/A	Onshore, Offshore	Onshore, Offshore
Solar (7)	Electricity	Variable	N/A	Photovoltaic, Concentrating Solar Thermal (0, 6, 12 hrs storage)	Photovoltaic, Concentrating Solar Thermal (0, 6, 12 hrs storage)
Geothermal (8)	Electricity	Dispatchable	N/A	Geothermal Plant	Closed-loop cooling
Petroleum (9)	Transport	Dispatchable, Default	Conventional, Oil Sands	ICE, Hybrid	ICE, Hybrid

Table 19 (Continued)

Ethanol (10)	Transport	Dispatchable	Corn	ICE, Hybrid	ICE, Hybrid
Biodiesel (11)	Transport	Dispatchable	Soy, Algae	ICE	ICE
Natural Gas (12)	Transport	Dispatchable	CNG	ICE	ICE
Hydrogen (13)	Transport	Dispatchable	Methane reforming	Fuel Cell	Fuel Cell
Electricity (14)	Transport	Dispatchable	Regional Grid	Battery Vehicle	Battery Vehicle
Coal (15)	Heating	Dispatchable	Underground, Surface	Boiler/Furnace	Boiler/Furnace
Natural Gas (16)	Heating	Dispatchable, Default	Conventional, Shale gas	Boiler/Furnace	Boiler/Furnace
Petroleum (17)	Heating	Dispatchable	Conventional, Oil Sands	Boiler/Furnace	Boiler/Furnace
Biomass (18)	Heating	Annual variation	Woody biomass	Boiler/Furnace	Boiler/Furnace
Surface Water (19)	Water	Annual variation	Local surface pumping	Irrigation/process pumps, Treatment plant	No treatment, Basic treatment Advanced Treatment
Ground Water (20)	Water	Dispatchable, Default	Local well pumping	Irrigation/process pumps, Treatment plant	No treatment, Basic treatment Advanced Treatment
Imported Water (21)	Water	Dispatchable	Pumped canal projects (CAP)	Irrigation/process pumps, Treatment plant	No treatment, Basic treatment Advanced Treatment
Desalination (22)	Water	Dispatchable	Local pumping	Treatment plant	Basic treatment Advanced Treatment
Trickling (23)	Wastewater	Dispatchable	N/A	WWTP	Trickling filter
Basic Treatment (24)	Wastewater	Dispatchable, Default	N/A	WWTP	Basic treatment w/ disinfection
Adv. Treatment, no De-N (25)	Wastewater	Dispatchable	N/A	WWTP	Treatment with anaerobic digestion
Adv. Treatment, w/ De-N (26)	Wastewater	Dispatchable	N/A	WWTP	Anaerobic digestion & De-N, Industrial treatment

Table 20: Example of regional capacity data inputs (PA-BAU scenario)

	Source Flag	*% fuel from region*	*2010 Fraction of Class*	*2010 Regional Capacity (MW, MJ/hr, m^3/hr)*	*Fleet CF*	*Fleet Eff.*	$p_{s,p}$	$p_{s,n}$
Coal	0	0.8	0.48	21636	0.56	0.35	1	1
Natural Gas	1	0.5	0.13	10875	0.30	0.41	1	1
Oil	2	0.01	0.0046	3679	0.016	0.27	0.1	1
Nuclear	3	0	0.35	10015	0.88	0.30	1	1
Hydro	4	1	0.0089	2042	0.11	0.97	1	1.8
Biomass	5	0.95	0.010	717.4	0.56	0.28	1	1.6
Wind	6	1	0.0049	748	0.16	0.97	1	0.98
Solar	7	1	0.000016	17.3	0.14	0.97	1	0.56
Geothermal	8	1	0	0.00001	0.30	0.97	1	0.91
Petroleum	9	0.01	0.95	2554000000	1	0.99	1	1
Ethanol	10	0.2	0.039	305480000	1	0.99	1	1
Biodiesel	11	0.7	0.012	25570000	1	0.99	1	1
CNG	12	0.5	0.00000034	83000000	1	0.92	1	1
Hydrogen	13	0.5	0.0000000001	282	1	0.97	1	1
Electric	14	1	0.000000003	8460	0.20	0.99	1	1
Coal	15	0.8	0.19	23016920.472	1	0.99	1	1
Natural Gas	16	0.5	0.58	70755718.488	1	0.92	1	1
Oil	17	0.01	0.17	20703050.16	1	0.99	1	1
Biomass	18	1	0.057	6941610.936	1	0.97	1	1
Water-Surface	19	1	0.94	1616000	0.87	0.97	1	1
Water-Ground	20	1	0.16	98500	0.95	0.97	1	1
Water-Import	21	1	0	0.0000001	0.90	0.97	1	1
Water-Desal	22	1	0	0.0000001	0.90	0.97	1	1
WW-Trickling	23	1	0.05	16151.05	0.75	0.97	1	1
WW-Aerated	24	1	0.50	161510.5	0.90	0.97	1	1
WW-Adv-NoDeN	25	1	0.40	129208.4	0.80	0.97	1	1
WW-Adv-DeN	26	1	0.05	16151.05	0.70	0.97	1	1

Table 21: Example of known capacity changes (PA-BAU scenario)

Source Flag	*Capacity (MW)*	*Capacity Factor*	*Heat Rate Efficiency*	*Year*	*Constr. Time*	*Ops Mode*	*Plant Mode*	*Fuel Mode*	*Interact Flag*[1]
0	-326	0.20	0.33	2012	0	0	0	1	-2
0	-510	0.078	0.27	2012	0	0	0	1	-2
0	-363	0.15	0.25	2012	0	0	0	1	-2
0	-632	0.41	0.34	2015	0	0	0	1	-2
0	-261	0.41	0.34	2015	0	0	0	1	-2
0	-420	0.42	0.34	2015	0	0	0	1	-2
0	-354	0.20	0.30	2015	0	0	0	1	-2
0	-490	0.25	0.26	2014	0	0	0	1	-2
0	-50	0.52	0.22	2011	0	0	0	1	1
0	-420	0.14	0.27	2011	0	0	0	1	-2
6	50	0.25	0.97	2012	1	0	0	0	-2
6	48	0.20	0.97	2012	2	0	0	0	-2
6	69	0.25	0.97	2012	2	0	0	0	-2
7	10	0.15	0.97	2012	1	0	0	0	-2
6	161	0.25	0.97	2012	2	0	0	0	-2
6	139	0.20	0.97	2012	2	0	0	0	-2
6	61	0.25	0.97	2012	2	0	0	0	-2
1	560	0.50	0.40	2011	3	0	0	0	0
7	5.5	0.15	0.97	2011	1	0	0	0	-2
4	5	0.50	0.97	2011	2	0	0	0	-2
1	98.5	0.50	0.97	2011	3	0	0	0	-2

1 – A positive interact flag assigns changes in the source mix to a specific source, a flag of -2 assigns changes across all sources in the same class, and a flag of -1 (not used here) assigns changes to the class default.

Table 22: Median US LCA impacts for operation stage

Source	*GHG*	*Energy*	*Water*	*Land*	*Cost*
Coal	8.30E+02	3.38E+01	1.41E+00	3.90E-10	8.03E+00
NG	5.00E+02	4.84E+01	1.16E+00	3.00E-08	5.02E+00
Oil	7.00E+02	6.30E+02	1.48E+00	3.00E-08	8.02E+00
Nuclear	4.00E+00	2.30E+01	1.78E+00	5.00E-09	1.73E+01
Hydro	1.15E+01	5.40E-01	2.26E+01	0.00E+00	3.75E+01
Biomass	2.50E+01	1.40E+02	1.49E+00	9.16E-06	1.05E+01
Wind	1.20E-01	4.00E+00	0	0	8.30E+01
Solar	2.00E+00	0	1.20E-01	0	7.50E+01
Geothermal	6.00E+01	1.41E+02	1.48E+00	0	2.00E+01
Petroleum	7.40E-02	7.53E-02	0	0	1.77E-02
EtOH	7.30E-02	7.50E-02	0	0	2.30E-02
Biodiesel	7.20E-02	7.50E-02	0	0	1.78E-02
CNG	5.80E-02	7.50E-02	0	0	7.80E-03
Hydrogen	1.00E-03	0	0	0	0.00E+00
Electric	1.00E-03	0	0	0	0.00E+00
Coal	8.90E-02	0	0	0	2.00E-02
NG	6.82E-02	0	0	0	8.50E-03
Petroleum	7.06E-02	0	0	0	2.22E-02
Biomass	6.82E-02	0	0	0	0.00E+00
Water-Surface	0	5.90E-01	0	0	1.36E-01
Water - Ground	0	1.23E+00	0	0	3.09E-01
Import	0	1.23E+00	0	0	3.09E-01
Desal	0	1.23E+00	0	0	3.09E-01
WW1	1.05E+00	8.10E-01	1.00E-02	0	1.10E-01
WW2	1.05E+00	1.00E+00	1.00E-02	0	5.00E-01
WW3	2.09E+00	1.23E+00	1.00E-02	0	1.14E+00
WW4	2.09E+00	1.52E+00	1.00E-02	0	1.50E+00

Table 23: Median US LCA impacts for construction stage

Source	*GHG*	*Energy*	*Water*	*Land*	*Cost*
Coal	2.24E+05	2.13E+06	2.27E+03	1.18E-03	3.00E+06
NG	4.74E+04	5.59E+06	2.81E+02	1.02E-03	6.65E+05
Oil	5.00E+04	7.56E+05	2.87E+02	1.02E-03	1.00E+06
Nuclear	2.97E+05	1.13E+07	3.46E+03	1.06E-03	5.50E+06
Hydro	3.91E+06	1.52E+07	9.68E+03	3.67E-01	1.15E+06
Biomass	4.00E+04	1.00E+06	3.00E+02	2.03E-03	2.00E+05
Wind	1.90E+05	5.20E+06	8.08E+03	2.00E-01	1.40E+06
Solar	5.04E+02	3.23E+07	1.10E+03	1.40E-02	4.00E+06
Geothermal	0	0	0	1.16E+00	4.14E+06
Petroleum	1.36E+03	2.46E+04	1.56E+01	0	3.35E+03
EtOH	1.36E+03	2.46E+04	1.56E+01	0	3.35E+03
Biodiesel	1.36E+03	2.46E+04	1.56E+01	0	3.35E+03
CNG	1.36E+03	2.46E+04	1.56E+01	0	3.45E+03
Hydrogen	1.36E+03	2.46E+04	1.56E+01	0	3.60E+03
Electric	1.36E+03	2.46E+04	1.56E+01	0	3.60E+03
Coal	0	0	0	0	0
NG	4.22E+00	7.60E+01	3.10E+01	0	6.32E+01
Petroleum	4.22E+00	7.60E+01	3.10E+01	0	6.32E+01
Biomass	4.22E+00	7.60E+01	3.10E+01	0	1.90E+02
Water-Surface	2.13E+04	2.03E+05	2.15E+02	1.04E-06	2.75E+01
Water - Ground	2.13E+04	2.03E+05	2.15E+02	1.04E-06	2.75E+01
Import	3.88E+03	3.69E+04	3.90E+01	0	5.00E+00
Desal	3.88E+03	3.69E+04	3.90E+01	0	5.00E+00
WW1	3.88E+04	3.69E+05	3.91E+02	2.07E-06	1.00E+02
WW2	3.88E+04	3.69E+05	3.91E+02	2.07E-06	5.00E+01
WW3	3.88E+04	3.69E+05	3.91E+02	2.07E-06	1.50E+02
WW4	3.88E+04	3.69E+05	3.91E+02	2.07E-06	2.10E+02

Table 24: Median US LCA impacts for fuel production

Source	*GHG*	*Energy*	*Water*	*Land*	*Cost*
Coal	1.32E+02	2.47E+02	8.40E-02	3.08E-08	4.00E+01
NG	1.00E+02	1.83E+02	2.58E-02	2.16E-07	7.95E+01
Oil	9.30E+01	3.28E+02	1.10E-03	0	2.77E+01
Nuclear	1.10E+01	1.29E+02	1.85E-01	4.30E-08	6.68E+00
Hydro	0	0	0	0	0
Biomass	5.10E+01	1.23E+02	0	2.14E-07	0
Wind	0	0	0	0	0
Solar	0	0	0	0	0
Geothermal	0	0	0	0	0
Petroleum	2.05E-02	2.33E-01	2.90E-05	2.00E-10	9.00E-03
EtOH	-8.40E-03	1.23E+00	4.10E-03	1.25E-07	0
Biodiesel	-5.40E-02	3.15E-01	3.26E-02	1.17E-07	0
CNG	2.80E-02	1.77E-01	0	2.67E-11	4.70E-03
Hydrogen	1.42E-01	8.20E-01	7.27E-04	0	2.72E-02
Electric	0	0	0	0	0
Coal	1.45E-02	2.40E-02	8.16E-06	4.00E-11	3.90E-03
NG	9.00E-03	6.50E-02	0	2.67E-11	4.70E-03
Petroleum	2.00E-02	2.08E-01	2.70E-04	2.00E-14	0
Biomass	-5.82E-02	0	0	5.90E-11	2.40E-02
Water-Surface	0	1.16E-01	0	2.00E-08	0
Water - Ground	0	4.00E-01	0	2.00E-08	0
Import	0	1.17E+01	5.00E-02	2.00E-08	3.24E-01
Desal	3.89E+00	1.20E+01	2.00E-01	2.00E-07	5.83E-01
WW1	0	0	0	0	0
WW2	0	0	0	0	0
WW3	0	0	0	0	0
WW4	0	0	0	0	0

B.2 VALIDATION RESULTS FOR PA AND AZ

Table 25: Model and Actual GHG Emissions for Pennsylvania Energy Supplies, 1990-2010

EIA data cover only fossil fuel combustion and are taken from SEDS [227], PA Study data are life-cycle scope and are taken from [232].

Million Metric Tons CO_2-eq	*Total (PA Study)*	*Elec Adj. (EIA)*	*Elec. (Model)*	*Transp. (EIA)*	*Transp. Operations (Model)*	*Transp. Indirect (Model)*	*Heat (EIA)*	*Heat (Model)*
1990	248	68.2	79.4	59.3	61.6	78.2	99.7	82.4
1991		67.3	78.6	59.2	62.4	82.0	93.8	81.9
1992		67.4	78.2	60.5	62.7	80.1	100.7	81.9
1993		69.6	77.5	62.1	63.1	80.5	100.3	82.0
1994		67.1	76.7	62.3	63.5	80.9	101.2	82.0
1995		69.0	75.8	63.0	63.9	81.2	100.1	82.1
1996		72.3	77.0	62.5	64.5	82.7	100.9	82.1
1997		73.3	78.1	65.3	65.2	83.5	97.9	82.2
1998		75.1	79.2	67.4	65.9	84.3	82.0	82.3
1999	255	72.4	80.5	68.0	66.6	85.1	83.9	82.3
2000		77.3	81.7	70.2	67.3	85.9	87.2	82.4
2001		70.7	82.2	70.0	68.6	90.8	84.7	82.2
2002		75.5	82.5	70.4	69.7	91.2	83.5	82.0
2003		75.9	83.0	68.9	70.9	91.8	87.4	81.9
2004		77.8	83.2	71.1	72.1	92.2	85.8	81.7
2005		80.9	83.5	72.4	73.1	92.7	83.1	81.5
2006		80.5	81.1	72.1	75.1	101.0	78.3	80.9
2007		82.0	78.9	71.8	76.8	100.1	79.6	80.3
2008		78.5	76.0	68.0	78.3	99.3	76.1	79.7
2009		73.7	73.9	66.5	79.7	98.6	66.2	79.1
2010	245	77.7	71.4	66.5	80.8	98.0	70.5	78.5

Table 26: Model and Actual Energy Costs for Arizona, 1990-2010

Costs are taken from SEDS, and have been adjusted for inflation using annual consumer price index [227].

2010 Dollars	*Electricity (Model)*	*Energy (Model)*	*Electricity (EIA)*	*Energy (EIA)*
1990	2.80E+09	1.56E+10	5.31E+09	1.08E+10
1991	2.96E+09	1.62E+10	5.20E+09	1.03E+10
1992	3.20E+09	1.68E+10	5.46E+09	1.08E+10
1993	3.40E+09	1.74E+10	5.50E+09	1.11E+10
1994	3.59E+09	1.79E+10	5.51E+09	1.11E+10
1995	3.79E+09	1.85E+10	5.29E+09	1.10E+10
1996	4.03E+09	1.93E+10	5.46E+09	1.18E+10
1997	3.33E+09	1.94E+10	5.46E+09	1.16E+10
1998	3.50E+09	2.03E+10	5.47E+09	1.12E+10
1999	3.69E+09	2.12E+10	5.46E+09	1.18E+10
2000	3.86E+09	2.22E+10	5.61E+09	1.34E+10
2001	3.98E+09	2.27E+10	5.57E+09	1.31E+10
2002	4.09E+09	2.33E+10	5.47E+09	1.27E+10
2003	4.21E+09	2.38E+10	5.58E+09	1.41E+10
2004	4.32E+09	2.44E+10	5.75E+09	1.60E+10
2005	4.41E+09	2.49E+10	6.04E+09	1.86E+10
2006	4.09E+09	2.45E+10	6.53E+09	2.04E+10
2007	4.10E+09	2.44E+10	6.93E+09	2.12E+10
2008	4.11E+09	2.42E+10	7.04E+09	2.28E+10
2009	4.13E+09	2.41E+10	7.13E+09	1.78E+10
2010	4.15E+09	2.40E+10	7.06E+09	1.94E+10

Table 27: Model and Actual GHG Emissions for Arizona Energy Supplies, 1990-2010

EIA data cover only fossil fuel combustion and are taken from SEDS [227]. AZ study data are life-cycle totals and taken from a state assessment done using EPA modeling approaches [233].

Million Metric Tons CO_2-eq	***Total (AZ Study)***	***Elec. (EIA)***	***Elec. (Model)***	***Transp. (EIA)***	***Transp. Operations (Model)***	***Transp. Indirect (Model)***	***Heat (EIA)***	***Heat***
1990	66	21.5	21.5	22.7	24.8	31.6	7.5	10.8
1991		21.7	22.4	23.3	25.6	32.6	7.6	11.1
1992		23.3	23.7	23.6	26.3	33.6	7.5	11.4
1993		24.5	24.7	24.9	27.0	34.5	7.4	11.7
1994		25.4	25.7	25.6	27.7	35.4	8.0	12.0
1995		21.7	26.7	26.1	28.5	36.3	8.2	12.3
1996		21.7	28.1	27.6	29.8	38.0	8.4	12.3
1997		23.6	29.7	27.6	31.9	44.8	8.7	12.4
1998		25.2	31.0	29.8	34.1	47.5	9.1	12.5
1999		26.6	32.2	31.5	36.3	50.0	9.0	12.6
2000	89	29.8	33.5	32.3	38.4	52.5	9.0	12.7
2001		30.6	34.1	33.3	39.8	52.6	9.1	12.4
2002		29.9	34.6	34.2	41.3	54.2	8.5	12.2
2003		30.7	35.1	35.0	42.7	55.8	8.2	11.9
2004		34.4	35.7	36.1	44.2	57.4	8.8	11.6
2005		33.8	36.1	36.8	45.6	59.0	9.1	11.4
2006		35.1	35.3	38.1	45.3	57.3	9.2	11.1
2007		36.7	34.6	37.8	45.1	56.7	9.2	10.8
2008		38.3	34.1	35.4	44.8	56.0	10.2	10.5
2009		34.8	33.6	33.5	44.6	55.4	8.7	10.1
2010		36.2	32.9	32.1	44.3	54.8	9.5	9.9

Table 28: Model and Actual energy costs for Pennsylvania, 1990-2010

Costs are taken from SEDS, and have been adjusted for inflation using annual consumer price index [227].

2010 Dollars	*Electricity (Model)*	*Energy (Model)*	*Electricity (EIA)*	*Energy (EIA)*
1990	9.23E+09	5.02E+10	1.45E+10	3.70E+10
1991	9.29E+09	5.05E+10	1.48E+10	3.59E+10
1992	9.37E+09	5.08E+10	1.44E+10	3.51E+10
1993	9.42E+09	5.11E+10	1.42E+10	3.44E+10
1994	9.46E+09	5.14E+10	1.41E+10	3.46E+10
1995	9.50E+09	5.16E+10	1.42E+10	3.43E+10
1996	9.57E+09	5.20E+10	1.40E+10	3.49E+10
1997	9.64E+09	5.24E+10	1.38E+10	3.47E+10
1998	9.71E+09	5.28E+10	1.36E+10	3.14E+10
1999	9.78E+09	5.32E+10	1.32E+10	3.08E+10
2000	9.87E+09	5.36E+10	1.17E+10	3.65E+10
2001	9.92E+09	5.42E+10	1.25E+10	3.66E+10
2002	9.96E+09	5.47E+10	1.30E+10	3.46E+10
2003	1.00E+10	5.53E+10	1.33E+10	3.78E+10
2004	9.87E+09	5.56E+10	1.29E+10	4.13E+10
2005	9.91E+09	5.61E+10	1.27E+10	4.74E+10
2006	9.83E+09	5.68E+10	1.31E+10	5.00E+10
2007	9.65E+09	5.73E+10	1.32E+10	5.14E+10
2008	9.53E+09	5.78E+10	1.38E+10	5.56E+10
2009	9.37E+09	5.81E+10	1.41E+10	4.39E+10
2010	9.28E+09	5.84E+10	1.36E+10	4.87E+10

APPENDIX C

SUPPORTING INFORMATION FOR BRAZILIAN APPLICATION OF REWSS

Table 29: Input data for the BAU case for Brazil (TWh)

TWh	*2010*	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*
Coal	12.2	31.4	29.5	31.4	31.4	31.4	31.4
Natural Gas	74.7	128.2	125.8	200.9	200.9	200.9	250.4
Oil	2	0	0	0	0	0	0
Nuclear	14.9	22.3	22.3	22.3	22.3	22.3	22.3
Conv. Hydropower	378.6	381.1	484.3	484.3	509.8	605.3	673.5
Biomass	15.8	22.6	22.6	35.8	62.6	75.7	88.9
Wind	1.6	8.5	10.8	18.1	24.5	29.8	34.4
Solar	0	0	0	0	0	0	0
Total Demand (TWh)	500	594	695	793	852	965	1101

Table 30: Source constants for Brazilian scenarios

Source	*Minimum Capacity (MW)*	*Construction Time (yr)*
Coal	300	4
Natural gas	100	3
Petroleum	100	3
Nuclear	1,200	10
Hydro	1,000	5
Biomass	100	2
Wind	10	1
Solar	0.05 (PV), 50 (CST)	1 (PV), 3 (CST)

Table 31: Brazilian modeling assumptions by source

Source	*Modes*		*Notes*
	Operation & Construction	**Fuel**	*(c.f. = capacity factor)*
Hydropower	Temperate Tropical	N/A	See Section 5.2.1 for details.
Natural Gas	Combined-cycle Steam turbine	Pipeline LNG	80% from pipelines, 20% from LNG. C.f.s up to 70% with up to 50% efficiency for CC plants
Nuclear	Once-through cooling	Centrifuge	Brazilian uranium with BR/EU enrichment. Only Angra complex modeled as no future plants planned.
Biomass	Steam turbine	Bagasse	Only sugarcane bagasse considered as energy source, and only grid exports included in impacts - no impacts for internal use. Impacts done by allocation between co-products.
Wind	Onshore	N/A	Production in Brazil, installation onshore with c.f.s of 25-40%
Solar	Concentrating Thermal (w/ 0, 6, 12 hrs of storage) Photovoltaics Hybrid CST	N/A	CST storage impacts doubled or removed from an example w/ 6hrs of storage to obtain impacts for plants w/ 0 and 12hr storage. Mean c.f.s of 45%, 30%, and 60%, respectively. Photovoltaics with c.f. of 12-17%, with manufacturing outside of BR.
Coal	Steam turbine	Surface Underground	90% from surface mining, with thermal efficiencies for new plants up to 40%, and c.f.s up to 70%.

Table 32: Data sources for Brazilian LCA information

Impact /Source	***GWP***	***Energy Consumption***	***Water Consumption***	***Land Occupation***	***Cost***	***Performance Parameters***
Units	**kg CO_2-eq**	**MJ**	**m^3**	**km^2**	**2010 $USD**	**%**
Hydro	[76, 137, 201, 202]	[76, 136, 234]	[110, 136]	[235]	[184, 207]A	[132, 184]
Natural Gas	[58, 170]	[136]	[119]	[54]	[184, 207]	[58, 184]
Nuclear	[13, 68, 190]	[136]	[119, 136]	[54]	[184, 207]	[184]
Biomass	[236]	[136, 209]	[119, 120]	[54, 120, 209]	[207, 236]	[184]
Coal	[56, 189]	[136]	[119]	[54]	[184, 207]	[58, 184]
Wind	[136, 192]	[237]	[136]	[54, 136]	[184, 207]	[184, 237]
Solar	[68, 73]	[73, 136]	[73, 136]	[238, 239]	[184, 207]	[73, 184]

Table 33: Median unit LCA values for Brazil in 2010

Stage	*Impact Category*	*Global Warming Potential*	*Energy Consumption*	*Water Consumption*	*Land Occupation*	*Economic Cost*
	Source	**kg CO_2-eq**	**MJ**	**m^3**	**km^2**	**2010 USD**
Generation (Impacts/MWh)	**Coal**	980	34	2.5	3.9E-10	83
	Natural Gas	500	48	1.1	3.0E-08	64
	Oil	700	630	1.5	3.0E-08	64
	Nuclear	12	23	2.1	5.0E-09	112
	Hydro	54	0.54	23	0	38
	Biomass	25	140	1.5	9.2E-06	11
	Wind	1.3	4	0	0	83
	Solar	2	0	0.12	0	75
Construction (Impacts/MW)	**Coal**	3.3E+05	4.7E+06	2.6E+03	2.9E-03	1.4E+06
	Natural Gas	4.9E+04	7.8E+05	3.0E+02	1.0E-03	6.0E+05
	Oil	--------	--------	--------	--------	--------
	Nuclear	6.6E+05	1.1E+07	3.5E+03	4.1E-04	5.5E+06
	Hydro	3.9E+06	1.5E+07	9.7E+03	3.8E-01	1.2E+06
	Biomass	4.0E+04	1.0E+06	3.0E+02	2.0E-03	1.1E+06
	Wind	6.2E+05	1.1E+07	5.0E+03	1.2E-01	1.1E+06
	Solar	1.8E+06	3.2E+07	1.1E+04	1.4E-02	4.0E+06
Fuel Production (Impacts/MWh)	**Coal**	144	2.5E+02	8.4E-02	3.7E-07	40
	Natural Gas	102	3.3E+02	9.7E-02	2.3E-07	80
	Oil	93	3.3E+02	0	0	160
	Nuclear	15	1.3E+02	3.5E-01	4.3E-08	23
	Hydro	0	0	0	0	0
	Biomass	51	1.2E+02	1.4E+01	*	0
	Wind	0	0	0	0	0
	Solar	0	0	0	0	0

Table 34: Production of ethanol from hydrolysis in BIO side case (ML)

Year	*Share in total ethanol production*	*Production of ethanol from hydrolysis*
2010	-	-
2015	-	-
2020	5%	2,496
2025	5%	3,016
2030	5%	4,046
2035	10%	11,728
2040	10%	15,580

Table 35: Installed generation capacity in the Solar side case (MW)

Year	CST	CST 6h	CST 12h	Solar PV	Solar Hybrid	Total
2010	0	0	0	0	0	0
2015	0	0	0	0	0	0
2020	0	0	0	100	800	900
2025	400	400	0	300	1600	2700
2030	400	800	800	500	2000	4500
2035	400	1200	1600	5000	2400	10600
2040	400	2400	1600	10000	2800	17200

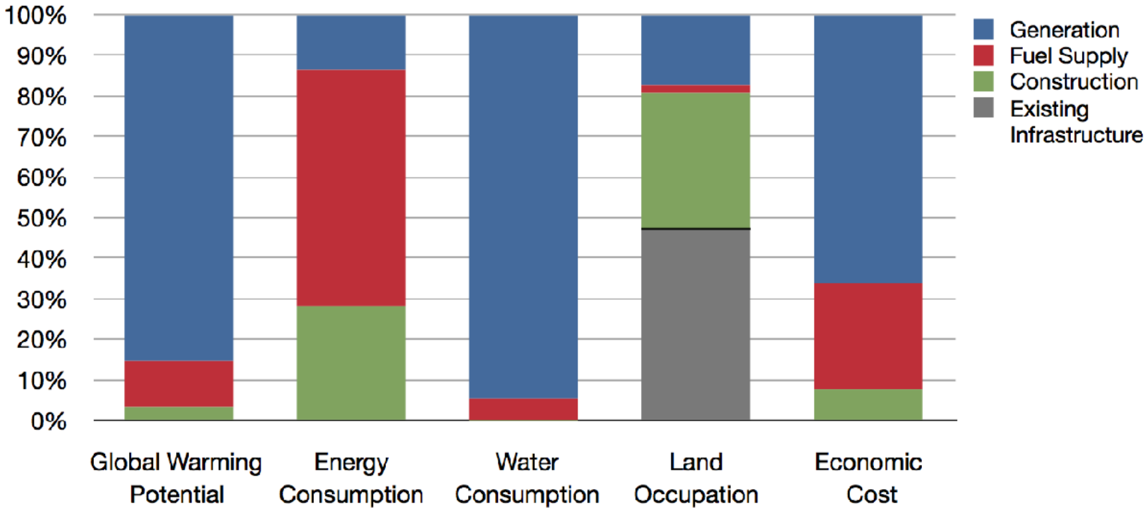

Figure 37: Cumulative per-stage impacts of BAU Brazilian case

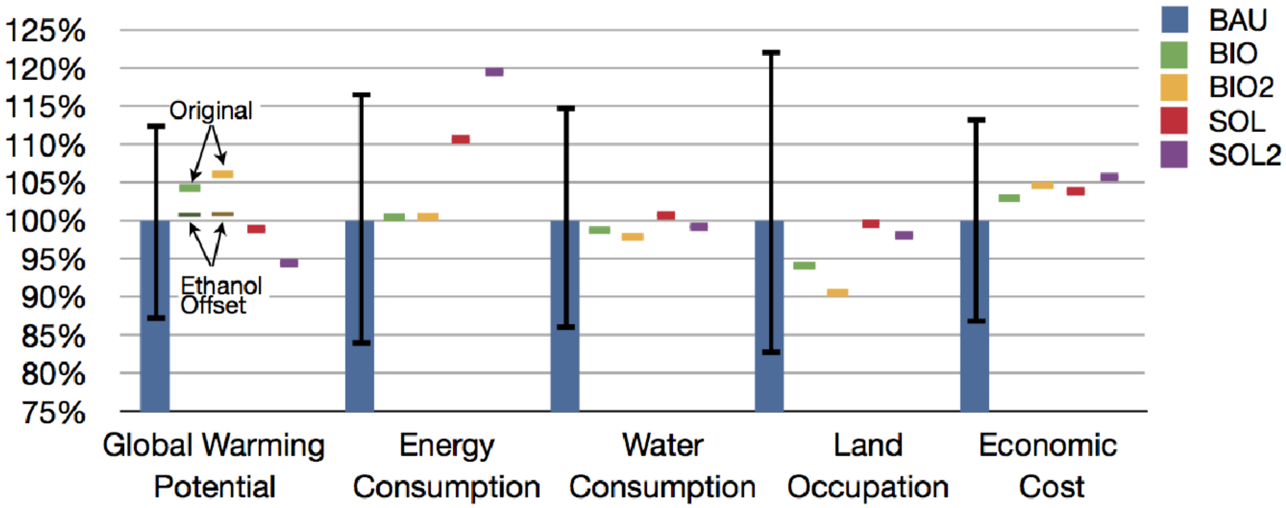

Figure 38: Cumulative impacts for Brazilian electricity cases

APPENDIX D

SUPPORTING INFORMATION FOR PA AND AZ APPLICATIONS OF REWSS

Table 36: Data sources for built-in US sources

Source	*Basic Parameters*	*Fuel Production*	*Construction*	*Operations*
Coal	[183]	[189] [54, 176]	[54, 98, 136]	[54, 189]
Natural Gas	[183]	[54, 240] [176]	[136] [54] [98]	[58]
Petroleum	[183]	[176]	[136] [54] [98]	[58]
Nuclear	[183]	[54, 190] [176]	[136] [54] [98]	[190]
Hydropower	[183]	N/A	[76, 136] [98]	[136]
Biomass	[183]	[54, 241] [176]	[98]	[241]
Wind	[183, 239]	N/A	[54, 192] [98] [239]	[192]
Solar	[183] [239]	N/A	[73] [54, 191] [98, 238] [239]	[73] [239, 242]
Geothermal	[239, 242]	N/A	[98] [239, 242]	[239, 242]
Petroleum	[146]	[176]	[243]	[146]
Ethanol	[146]	[61, 120] [176]	[243]	[146]
Biodiesel	[146]	[230, 244, 245] [176]	[243]	[146]

Table 36 (Continued)

Natural Gas	[146]	[54, 240] [176]	[243]	[146]
Hydrogen	[146]	[246]	[243]	[146]
Electricity	[146]	N/A	[243]	[146]
Coal		[54, 240] [176]	[136]	[247, 248]
Natural Gas		[54, 240] [176]	[136]	[247, 248]
Petroleum		[176]	[136]	[247, 248]
Biomass		[176, 249]	[136, 249]	[247-249]
Surface Water	[3]	[83] [15]	[136]	[83] [15]
Ground Water	[3]	[83] [15]	[136]	[15, 83]
Imported Water	[3]	[130]	[136]	[83] [15]
Desalination	[3]	[130]	[136]	[122, 123]
Trickling	[196]	N/A	[136]	[15, 83]
Basic Treatment	[196]	N/A	[136]	[15, 83]
Adv. Treatment, no De-N	[196]	N/A	[136]	[15, 83]
Adv. Treatment, w/ De-N	[196]	N/A	[136]	[15, 83]

D.1 PENNSYLVANIA SCENARIOS RESULTS

Table 37: Pennsylvania BAU Scenario Results

		2010	***2015***	***2020***	***2025***	***2030***	***2035***
GWP (kg CO_2-eq)	**Elec**	6.69E+10	5.58E+10	5.18E+10	4.96E+10	5.05E+10	5.12E+10
	Trans	9.34E+10	9.27E+10	9.27E+10	9.27E+10	9.24E+10	9.21E+10
	Heat	9.11E+10	9.10E+10	9.14E+10	9.18E+10	9.21E+10	9.22E+10
	Water	1.14E+09	4.78E+08	4.43E+08	4.26E+08	4.41E+08	4.53E+08
	WasteW	3.54E+09	3.33E+09	3.37E+09	3.40E+09	3.40E+09	3.39E+09
Energy (MJ)	**Elec**	4.05E+10	3.32E+10	3.27E+10	3.13E+10	3.13E+10	3.31E+10
	Trans	3.50E+11	3.50E+11	3.50E+11	3.51E+11	3.56E+11	3.61E+11
	Heat	1.02E+11	1.01E+11	9.94E+10	9.85E+10	9.79E+10	9.69E+10
	Water	1.66E+10	1.11E+10	1.11E+10	1.11E+10	1.13E+10	1.14E+10
	WasteW	4.46E+09	3.15E+09	3.28E+09	3.20E+09	2.96E+09	2.90E+09
Water Consumption (m^3)	**Elec**	2.66E+08	2.52E+08	2.48E+08	2.49E+08	2.43E+08	2.39E+08
	Trans	6.59E+08	1.54E+09	1.52E+09	1.56E+09	1.74E+09	1.94E+09
	Heat	1.22E+08	7.14E+07	6.88E+07	6.73E+07	6.30E+07	6.23E+07
	Water	8.48E+06	2.19E+06	2.16E+06	2.18E+06	2.16E+06	2.15E+06
	WasteW	2.40E+07	2.20E+07	2.21E+07	2.20E+07	2.17E+07	2.16E+07
Land Occupation (annual, km^2)	**Elec**	2.97E+02	1.78E+02	2.31E+02	2.30E+02	2.32E+02	2.48E+02
	Trans	5.42E+03	5.80E+03	5.75E+03	5.89E+03	6.58E+03	7.32E+03
	Heat	3.57E+01	3.59E+01	3.63E+01	3.65E+01	3.66E+01	3.70E+01
	Water	1.62E+02	2.74E+02	2.74E+02	2.75E+02	2.79E+02	2.82E+02
	WasteW	2.67E-01	3.57E-01	5.10E-01	6.27E-01	6.58E-01	6.64E-01
Cost (Constant 2010 Dollars)	**Elec**	1.24E+10	1.06E+10	1.12E+10	1.12E+10	1.10E+10	1.13E+10
	Trans	3.16E+10	3.17E+10	3.17E+10	3.17E+10	3.17E+10	3.18E+10
	Heat	1.89E+10	1.88E+10	1.86E+10	1.85E+10	1.84E+10	1.83E+10
	Water	2.18E+09	2.12E+09	2.12E+09	2.13E+09	2.15E+09	2.18E+09
	WasteW	1.99E+09	1.97E+09	2.00E+09	2.04E+09	2.07E+09	2.07E+09
Land (cumulative, km^2)	**Elec**	1.14E+03	1.62E+03	1.86E+03	1.97E+03	1.98E+03	2.01E+03
	Trans	4.42E-06	9.40E-06	1.08E-05	1.52E-05	2.25E-05	2.61E-05
	Heat	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Water	1.23E+01	1.65E+01	1.85E+01	1.95E+01	1.98E+01	2.04E+01
	WasteW	3.90E+00	5.20E+00	5.89E+00	6.26E+00	6.32E+00	6.41E+00
kg CO_2-eq/MWh		301.02	252.82	235.06	224.89	229.19	232.47
% of water withdrawals consumed for energy (WfE)		7.44%	14.54%	14.40%	14.72%	16.06%	17.58%
% of water withdrawals consumed for elec (WfL)		1.89%	1.97%	1.94%	1.95%	1.91%	1.88%
% of energy demanded consumed for water (EfW)		0.68%	0.46%	0.46%	0.46%	0.46%	0.46%
% of elec consumed for water (LfW)		2.10%	1.44%	1.45%	1.44%	1.43%	1.44%

Table 38: Pennsylvania MSH Scenario Results

		2010	*2015*	*2020*	*2025*	*2030*	*2035*
GWP (kg CO_2-eq)	**Elec**	6.61E+10	5.12E+10	4.75E+10	4.50E+10	4.74E+10	4.88E+10
	Trans	9.34E+10	9.31E+10	9.30E+10	9.29E+10	9.25E+10	9.21E+10
	Heat	9.22E+10	9.10E+10	9.09E+10	9.10E+10	9.11E+10	9.10E+10
	Water	1.02E+09	4.72E+08	4.40E+08	4.20E+08	4.42E+08	4.55E+08
	WasteW	3.39E+09	3.32E+09	3.35E+09	3.38E+09	3.39E+09	3.39E+09
Energy (MJ)	**Elec**	4.31E+10	3.44E+10	3.27E+10	3.26E+10	3.45E+10	3.34E+10
	Trans	3.50E+11	3.47E+11	3.44E+11	3.42E+11	3.40E+11	3.39E+11
	Heat	1.02E+11	9.87E+10	9.70E+10	9.67E+10	9.64E+10	9.54E+10
	Water	1.49E+10	1.09E+10	1.09E+10	1.08E+10	1.08E+10	1.08E+10
	WasteW	3.88E+09	3.19E+09	3.28E+09	3.20E+09	2.96E+09	2.90E+09
Water Consumption (m^3)	**Elec**	2.65E+08	2.55E+08	2.51E+08	2.51E+08	2.39E+08	2.33E+08
	Trans	6.59E+08	9.92E+08	9.37E+08	9.21E+08	9.31E+08	9.57E+08
	Heat	1.38E+08	8.88E+07	5.50E+07	5.57E+07	5.42E+07	5.57E+07
	Water	7.58E+06	4.68E+06	4.63E+06	4.64E+06	4.53E+06	4.49E+06
	WasteW	2.28E+07	2.21E+07	2.21E+07	2.20E+07	2.17E+07	2.16E+07
Land Occupation (annual, km^2)	**Elec**	3.51E+02	1.81E+02	2.35E+02	2.33E+02	2.13E+02	2.15E+02
	Trans	5.42E+03	5.31E+03	5.01E+03	4.93E+03	4.97E+03	5.12E+03
	Heat	3.57E+01	3.63E+01	3.67E+01	3.68E+01	3.68E+01	3.72E+01
	Water	1.47E+02	2.65E+02	2.65E+02	2.65E+02	2.64E+02	2.64E+02
	WasteW	2.67E-01	3.61E-01	5.19E-01	6.38E-01	6.04E-01	6.07E-01
Cost (Constant 2010 Dollars)	**Elec**	1.32E+10	1.07E+10	1.11E+10	1.14E+10	1.06E+10	1.02E+10
	Trans	3.15E+10	3.14E+10	3.06E+10	3.00E+10	2.88E+10	2.79E+10
	Heat	1.89E+10	1.86E+10	1.84E+10	1.84E+10	1.84E+10	1.83E+10
	Water	1.96E+09	2.02E+09	2.02E+09	2.02E+09	2.01E+09	2.01E+09
	WasteW	1.94E+09	1.97E+09	2.00E+09	2.04E+09	2.07E+09	2.07E+09
Land (cumulative, km^2)	**Elec**	1.18E+03	1.70E+03	1.95E+03	2.05E+03	2.07E+03	2.07E+03
	Trans	4.63E-06	9.94E-06	1.10E-05	1.49E-05	2.12E-05	2.36E-05
	Heat	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Water	1.18E+01	1.65E+01	1.85E+01	1.93E+01	1.94E+01	1.95E+01
	WasteW	3.95E+00	5.41E+00	6.15E+00	6.51E+00	6.58E+00	6.59E+00
kg CO_2-eq/MWh		299.51	231.95	215.58	204.31	215.32	221.54
% of water withdrawals consumed for energy (WfE)		8.31%	10.44%	9.72%	9.61%	9.59%	9.76%
% of water withdrawals consumed for elec (WfL)		2.07%	1.99%	1.96%	1.96%	1.87%	1.83%
% of energy demanded consumed for water (EfW)		0.60%	0.45%	0.45%	0.45%	0.44%	0.44%
% of elec consumed for water (LfW)		1.89%	1.42%	1.43%	1.42%	1.39%	1.39%

Table 39: Pennsylvania REN Scenario Results

		2010	*2015*	*2020*	*2025*	*2030*	*2035*
GWP (kg CO_2-eq)	**Elec**	6.65E+10	4.39E+10	4.16E+10	3.85E+10	3.71E+10	3.30E+10
	Trans	9.34E+10	9.28E+10	9.27E+10	9.27E+10	9.24E+10	9.19E+10
	Heat	9.14E+10	9.07E+10	9.07E+10	9.09E+10	9.10E+10	9.09E+10
	Water	1.01E+09	3.68E+08	3.56E+08	3.27E+08	3.17E+08	2.90E+08
	WasteW	3.39E+09	3.30E+09	3.34E+09	3.37E+09	3.36E+09	3.35E+09
Energy (MJ)	**Elec**	4.35E+10	4.25E+10	3.06E+10	3.12E+10	3.11E+10	4.48E+10
	Trans	3.50E+11	3.51E+11	3.50E+11	3.52E+11	3.60E+11	3.65E+11
	Heat	1.02E+11	9.89E+10	9.67E+10	9.65E+10	9.61E+10	9.38E+10
	Water	1.48E+10	1.10E+10	1.10E+10	1.10E+10	1.12E+10	1.14E+10
	WasteW	3.88E+09	3.18E+09	3.28E+09	3.19E+09	2.95E+09	2.88E+09
Water Consumption (m^3)	**Elec**	2.66E+08	2.53E+08	2.46E+08	2.47E+08	2.43E+08	2.32E+08
	Trans	6.60E+08	1.54E+09	1.53E+09	1.58E+09	1.81E+09	2.07E+09
	Heat	1.37E+08	7.36E+07	6.33E+07	5.88E+07	5.62E+07	6.89E+07
	Water	7.52E+06	2.12E+06	2.13E+06	2.12E+06	2.12E+06	2.05E+06
	WasteW	2.28E+07	2.20E+07	2.21E+07	2.20E+07	2.17E+07	2.16E+07
Land Occupation (annual, km^2)	**Elec**	4.02E+02	4.34E+02	2.60E+02	3.03E+02	3.14E+02	3.03E+02
	Trans	5.41E+03	5.81E+03	5.76E+03	5.94E+03	6.81E+03	7.78E+03
	Heat	3.58E+01	3.65E+01	3.72E+01	3.72E+01	3.73E+01	3.85E+01
	Water	1.48E+02	2.75E+02	2.75E+02	2.75E+02	2.80E+02	2.85E+02
	WasteW	2.69E-01	6.18E-01	6.57E-01	6.52E-01	6.45E-01	6.67E-01
Cost (Constant 2010 Dollars)	**Elec**	1.33E+10	1.49E+10	1.17E+10	1.28E+10	1.25E+10	1.52E+10
	Trans	3.15E+10	3.18E+10	3.16E+10	3.18E+10	3.22E+10	3.21E+10
	Heat	1.89E+10	1.85E+10	1.83E+10	1.82E+10	1.82E+10	1.80E+10
	Water	1.96E+09	2.11E+09	2.10E+09	2.12E+09	2.15E+09	2.18E+09
	WasteW	1.94E+09	1.97E+09	2.00E+09	2.05E+09	2.07E+09	2.07E+09
Land (cumulative, km^2)	**Elec**	1.19E+03	2.31E+03	2.53E+03	2.82E+03	3.16E+03	3.53E+03
	Trans	4.64E-06	3.07E-01	4.78E-01	1.20E+00	4.08E+00	6.85E+00
	Heat	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Water	1.18E+01	2.24E+01	2.42E+01	2.68E+01	3.02E+01	3.40E+01
	WasteW	3.95E+00	7.12E+00	7.78E+00	8.66E+00	9.68E+00	1.07E+01
kg CO_2-eq/MWh		301.38	199.15	188.49	174.55	168.27	149.65
% of water withdrawals consumed for energy (WfE)		8.31%	14.62%	14.38%	14.75%	16.53%	18.59%
% of water withdrawals consumed for elec (WfL)		2.08%	1.98%	1.92%	1.93%	1.90%	1.82%
% of energy demanded consumed for water (EfW)		0.60%	0.46%	0.46%	0.46%	0.45%	0.46%
% of elec consumed for water (LfW)		1.89%	1.43%	1.44%	1.43%	1.42%	1.44%

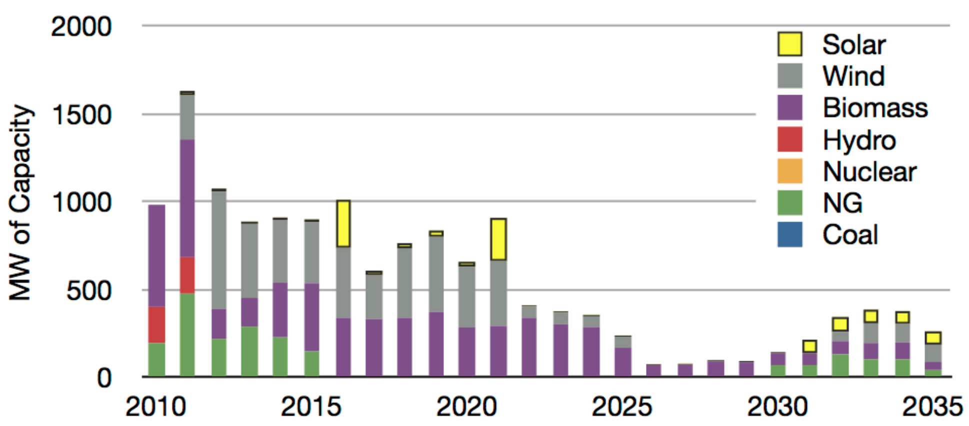

Figure 39: Electrical Capacity Additions, PA BAU Scenario

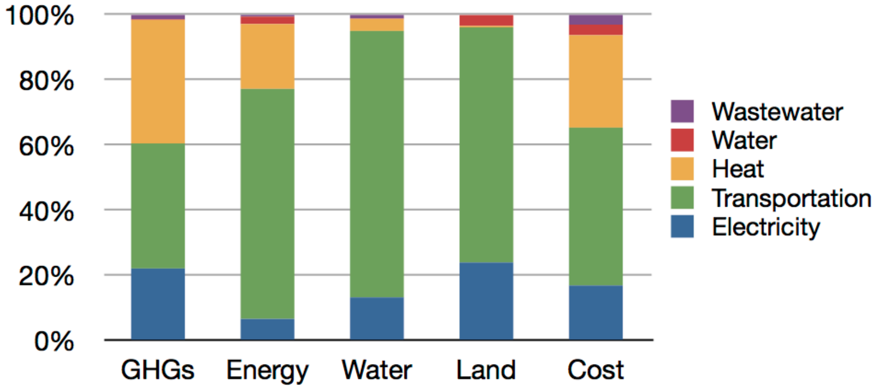

Figure 40: Cumulative Impacts by Class, PA BAU Scenario

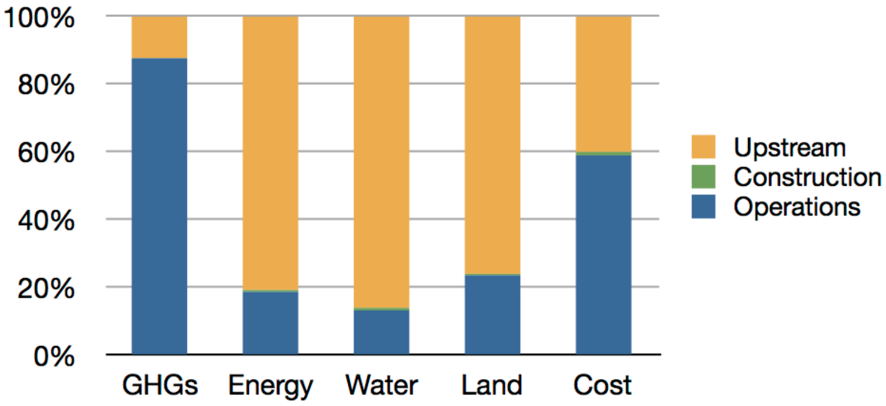

Figure 41: Cumulative Impacts by Stage, PA BAU Scenario

D.2 ARIZONA WATER SCENARIOS

Table 40: Arizona BAU Scenario Results

		2010	*2015*	*2020*	*2025*	*2030*	*2035*
GWP (kg CO_2-eq)	**Elec**	3.85E+10	3.44E+10	3.74E+10	3.84E+10	4.27E+10	4.48E+10
	Trans	4.24E+10	4.13E+10	4.14E+10	4.18E+10	4.36E+10	4.57E+10
	Heat	1.38E+10	1.43E+10	1.49E+10	1.52E+10	1.52E+10	1.54E+10
	Water	3.13E+08	3.04E+08	3.17E+08	4.85E+08	5.16E+08	4.20E+08
	WasteW	1.51E+09	1.72E+09	2.04E+09	2.38E+09	2.77E+09	3.03E+09
Energy (MJ)	**Elec**	1.67E+10	1.75E+10	2.10E+10	2.41E+10	2.56E+10	2.79E+10
	Trans	1.68E+11	1.64E+11	1.64E+11	1.66E+11	1.80E+11	1.94E+11
	Heat	2.17E+10	2.22E+10	2.28E+10	2.32E+10	2.31E+10	2.34E+10
	Water	3.43E+10	3.95E+10	4.33E+10	4.92E+10	5.35E+10	5.71E+10
	WasteW	2.85E+09	2.51E+09	2.98E+09	3.39E+09	3.84E+09	2.73E+09
Water Consumption (m^3)	**Elec**	1.60E+08	1.51E+08	1.71E+08	1.99E+08	2.02E+08	2.18E+08
	Trans	1.68E+08	1.75E+08	1.73E+08	1.78E+08	2.08E+08	2.43E+08
	Heat	3.05E+07	2.34E+07	2.49E+07	2.37E+07	2.13E+07	2.40E+07
	Water	1.27E+08	1.48E+08	1.63E+08	1.82E+08	1.99E+08	2.16E+08
	WasteW	8.71E+06	9.48E+06	1.13E+07	1.31E+07	1.51E+07	1.56E+07
Land Occupation (annual, km^2)	**Elec**	1.79E+01	5.23E+01	6.04E+01	9.12E+01	8.75E+01	9.57E+01
	Trans	3.55E+03	3.53E+03	3.50E+03	3.62E+03	4.20E+03	4.92E+03
	Heat	3.56E+00	3.78E+00	3.98E+00	4.06E+00	4.06E+00	4.20E+00
	Water	1.26E+02	1.39E+02	1.47E+02	1.55E+02	1.63E+02	1.71E+02
	WasteW	4.37E-02	9.39E-02	1.49E-01	2.16E-01	2.52E-01	2.81E-01
Cost (Constant 2010 Dollars)	**Elec**	4.28E+09	5.00E+09	5.97E+09	7.56E+09	7.71E+09	8.85E+09
	Trans	1.44E+10	1.41E+10	1.42E+10	1.42E+10	1.55E+10	1.63E+10
	Heat	3.24E+09	3.35E+09	3.45E+09	3.50E+09	3.48E+09	3.54E+09
	Water	1.68E+09	1.90E+09	2.06E+09	2.25E+09	2.45E+09	2.67E+09
	WasteW	8.38E+08	1.01E+09	1.20E+09	1.41E+09	1.64E+09	1.90E+09
Land (cumulative, km^2)	**Elec**	7.44E+02	9.73E+02	1.00E+03	1.04E+03	1.05E+03	1.09E+03
	Trans	3.48E-03	6.53E-03	6.07E-03	7.71E-03	1.12E-02	1.29E-02
	Heat	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Water	6.86E+00	9.14E+00	9.04E+00	9.16E+00	9.35E+00	9.66E+00
	WasteW	1.62E+00	2.42E+00	2.69E+00	3.01E+00	3.33E+00	3.70E+00
kg CO_2-eq/MWh		345.30	299.76	294.46	278.16	287.08	280.46
% of water withdrawals consumed for energy (WfE)		5.73%	5.08%	5.07%	5.24%	5.36%	5.74%
% of water withdrawals consumed for elec (WfL)		2.56%	2.53%	2.69%	2.91%	2.77%	2.86%
% of energy demanded consumed for water (EfW)		3.51%	3.94%	4.14%	4.51%	4.69%	4.63%
% of elec consumed for water (LfW)		7.40%	8.14%	8.11%	8.46%	8.58%	8.32%

Table 41: Arizona DES Scenario Results

		2010	*2015*	*2020*	*2025*	*2030*	*2035*
GWP (kg CO$_2$-eq)	**Elec**	3.85E+10	3.44E+10	3.77E+10	3.89E+10	4.34E+10	4.59E+10
	Trans	4.24E+10	4.13E+10	4.14E+10	4.18E+10	4.36E+10	4.57E+10
	Heat	1.38E+10	1.43E+10	1.49E+10	1.52E+10	1.52E+10	1.54E+10
	Water	3.22E+08	8.41E+08	1.86E+09	3.16E+09	4.48E+09	5.76E+09
	WasteW	1.51E+09	1.72E+09	2.04E+09	2.39E+09	2.78E+09	3.04E+09
Energy (MJ)	**Elec**	1.67E+10	1.72E+10	2.12E+10	2.44E+10	2.61E+10	2.85E+10
	Trans	1.68E+11	1.64E+11	1.64E+11	1.66E+11	1.80E+11	1.93E+11
	Heat	2.17E+10	2.22E+10	2.28E+10	2.32E+10	2.31E+10	2.34E+10
	Water	3.44E+10	4.16E+10	4.92E+10	5.92E+10	6.85E+10	7.68E+10
	WasteW	2.85E+09	2.51E+09	2.98E+09	3.39E+09	3.84E+09	2.73E+09
Water Consumption (m^3)	**Elec**	1.60E+08	1.51E+08	1.72E+08	2.02E+08	2.05E+08	2.23E+08
	Trans	1.67E+08	1.74E+08	1.72E+08	1.77E+08	2.08E+08	2.42E+08
	Heat	3.05E+07	2.34E+07	2.49E+07	2.37E+07	2.13E+07	2.40E+07
	Water	1.27E+08	1.75E+08	2.43E+08	3.21E+08	4.06E+08	4.99E+08
	WasteW	8.71E+06	9.48E+06	1.13E+07	1.31E+07	1.51E+07	1.56E+07
Land Occupation (annual, km^2)	**Elec**	1.79E+01	5.24E+01	6.09E+01	9.24E+01	8.93E+01	9.81E+01
	Trans	3.56E+03	3.54E+03	3.50E+03	3.63E+03	4.20E+03	4.92E+03
	Heat	3.56E+00	3.78E+00	3.98E+00	4.06E+00	4.06E+00	4.20E+00
	Water	1.26E+02	1.62E+02	2.15E+02	2.75E+02	3.41E+02	4.14E+02
	WasteW	4.38E-02	9.40E-02	1.51E-01	2.19E-01	2.57E-01	2.88E-01
Cost (Constant 2010 Dollars)	**Elec**	4.28E+09	4.96E+09	6.03E+09	7.66E+09	7.87E+09	9.07E+09
	Trans	1.44E+10	1.42E+10	1.42E+10	1.43E+10	1.55E+10	1.64E+10
	Heat	3.24E+09	3.34E+09	3.45E+09	3.50E+09	3.48E+09	3.54E+09
	Water	1.67E+09	2.00E+09	2.36E+09	2.79E+09	3.26E+09	3.79E+09
	WasteW	8.38E+08	1.01E+09	1.20E+09	1.41E+09	1.64E+09	1.90E+09
Land (cumulative, km^2)	**Elec**	7.47E+02	9.77E+02	1.01E+03	1.05E+03	1.07E+03	1.12E+03
	Trans	3.49E-03	6.55E-03	6.12E-03	7.84E-03	1.14E-02	1.33E-02
	Heat	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Water	6.89E+00	9.34E+00	9.59E+00	1.01E+01	1.07E+01	1.15E+01
	WasteW	1.63E+00	2.43E+00	2.71E+00	3.05E+00	3.39E+00	3.79E+00
kg CO$_2$-eq/MWh		344.89	300.33	296.81	281.83	292.27	287.05
% of water withdrawals consumed for energy (WfE)		5.72%	5.06%	5.08%	5.26%	5.40%	5.79%
% of water withdrawals consumed for elec (WfL)		2.56%	2.20%	2.37%	2.64%	2.55%	2.64%
% of energy demanded consumed for water (EfW)		3.52%	4.14%	4.67%	5.37%	5.92%	6.16%
% of elec consumed for water (LfW)		7.42%	8.55%	9.14%	10.07%	10.81%	11.06%

Table 42: Arizona DES+REN Scenario Results

		2010	*2015*	*2020*	*2025*	*2030*	*2035*
GWP (kg CO_2-eq)	**Elec**	3.85E+10	3.08E+10	3.19E+10	3.20E+10	3.31E+10	2.84E+10
	Trans	4.12E+10	4.38E+10	4.43E+10	4.60E+10	4.84E+10	5.08E+10
	Heat	1.38E+10	1.43E+10	1.47E+10	1.50E+10	1.50E+10	1.53E+10
	Water	3.22E+08	8.07E+08	1.81E+09	3.10E+09	4.39E+09	5.58E+09
	WasteW	1.51E+09	1.71E+09	2.03E+09	2.37E+09	2.75E+09	2.98E+09
Energy (MJ)	**Elec**	1.68E+10	1.82E+10	2.53E+10	2.87E+10	2.64E+10	7.36E+10
	Trans	1.63E+11	1.72E+11	1.75E+11	1.87E+11	2.11E+11	2.29E+11
	Heat	2.17E+10	2.17E+10	2.22E+10	2.26E+10	2.25E+10	2.27E+10
	Water	3.44E+10	4.15E+10	4.93E+10	5.94E+10	6.87E+10	7.68E+10
	WasteW	2.85E+09	2.51E+09	2.98E+09	3.39E+09	3.83E+09	2.71E+09
Water Consumption (m^3)	**Elec**	1.60E+08	1.61E+08	1.89E+08	2.26E+08	2.36E+08	2.66E+08
	Trans	1.61E+08	1.66E+08	1.79E+08	2.01E+08	2.35E+08	2.69E+08
	Heat	3.05E+07	2.48E+07	2.46E+07	2.13E+07	1.99E+07	2.21E+07
	Water	1.27E+08	1.75E+08	2.42E+08	3.21E+08	4.05E+08	4.95E+08
	WasteW	8.71E+06	9.50E+06	1.13E+07	1.32E+07	1.52E+07	1.56E+07
Land Occupation (annual, km^2)	**Elec**	1.79E+01	6.35E+01	8.23E+01	1.57E+02	1.06E+02	1.14E+02
	Trans	3.46E+03	3.49E+03	3.75E+03	4.17E+03	4.71E+03	5.39E+03
	Heat	3.56E+00	3.89E+00	4.12E+00	4.19E+00	4.19E+00	4.34E+00
	Water	1.26E+02	1.62E+02	2.15E+02	2.75E+02	3.42E+02	4.13E+02
	WasteW	4.37E-02	1.08E-01	1.94E-01	2.24E-01	2.60E-01	2.53E-01
Cost (Constant 2010 Dollars)	**Elec**	4.30E+09	5.69E+09	7.72E+09	9.72E+09	9.71E+09	2.01E+10
	Trans	1.40E+10	1.50E+10	1.51E+10	1.62E+10	1.87E+10	2.03E+10
	Heat	3.23E+09	3.31E+09	3.40E+09	3.45E+09	3.43E+09	3.49E+09
	Water	1.67E+09	2.01E+09	2.38E+09	2.81E+09	3.29E+09	3.81E+09
	WasteW	8.38E+08	1.01E+09	1.20E+09	1.41E+09	1.65E+09	1.91E+09
Land (cumulative, km^2)	**Elec**	7.48E+02	9.95E+02	1.05E+03	1.31E+03	1.49E+03	1.65E+03
	Trans	3.40E-03	2.24E-01	2.34E-01	6.35E-01	2.13E+00	3.49E+00
	Heat	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Water	6.89E+00	9.39E+00	9.85E+00	1.22E+01	1.42E+01	1.61E+01
	WasteW	1.63E+00	2.44E+00	2.78E+00	3.68E+00	4.50E+00	5.33E+00
kg CO_2-eq/MWh		344.97	265.87	249.22	228.78	219.16	174.71
% of water withdrawals consumed for energy (WfE)		5.63%	5.11%	5.40%	5.86%	6.10%	6.60%
% of water withdrawals consumed for elec (WfL)		2.56%	2.34%	2.60%	2.95%	2.93%	3.15%
% of energy demanded consumed for water (EfW)		3.56%	4.01%	4.52%	5.15%	5.68%	5.90%
% of elec consumed for water (LfW)		7.42%	8.44%	9.06%	9.98%	10.67%	10.85%

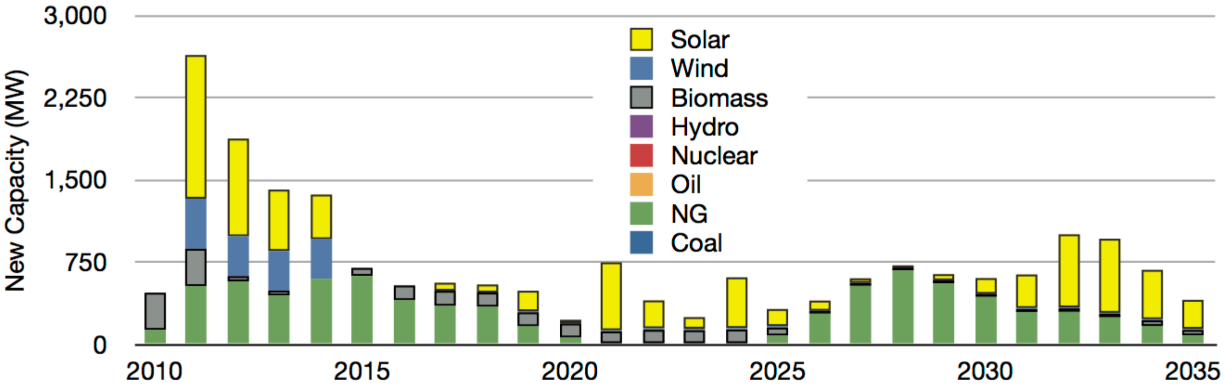

Figure 42: Electrical Capacity Additions, AZ BAU Scenario

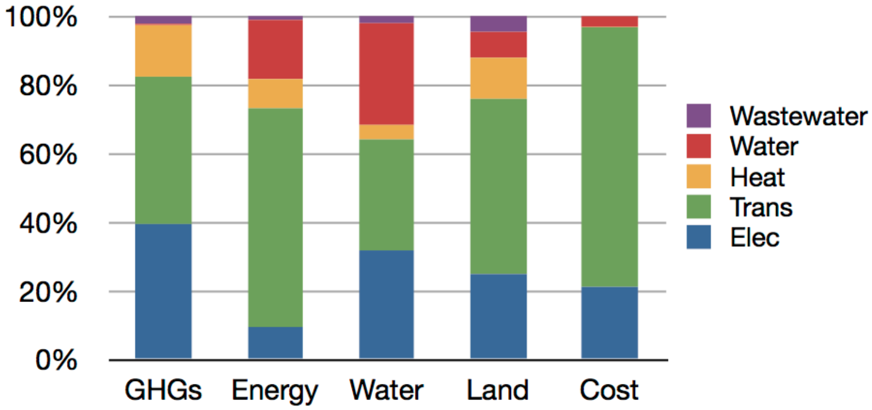

Figure 43: Cumulative Impacts by Demand Class, AZ BAU Scenario

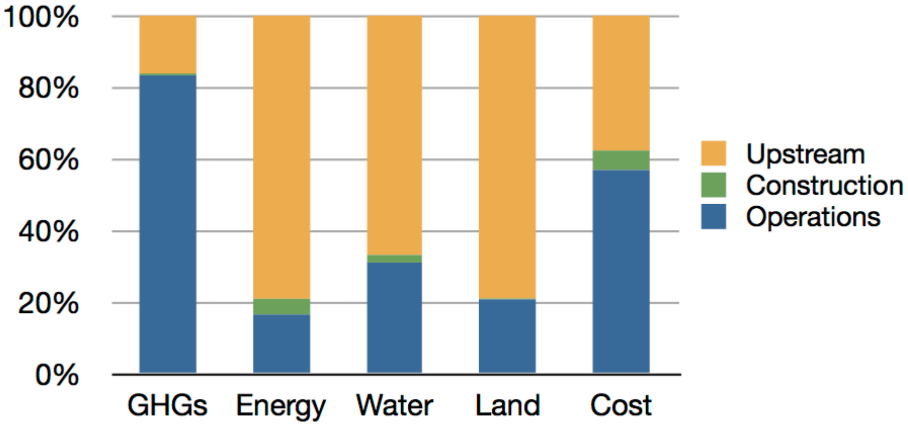

Figure 44: Cumulative Impacts by Stage, AZ BAU Scenarios

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