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Renewable Energy Landscapes: Approaches to Modeling Change in the Electrical System and Predicting the Influence on Urban Development and Environmental Resources

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By

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Abstract

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Professor John D. Radke, Chair

Of the major infrastructure systems upon which society relies, energy systems have been some of the most influential yet under recognized drivers of urban development and environmental degradation. Both energy consumption and the proportion of the population living in urban areas are projected to increase substantially over the next half-century. At the same time, in the context of the serious climate change challenges facing society, the energy sector is entering a period of significant transition in primary energy sources, turning from fossil fuels to a variety of renewable and low-carbon resources. Such a transformation will require dramatic changes in the technologies and networks via which electrical power is produced and delivered. These changes can in turn be expected to propagate new patterns of environmental impact across the landscape—both through direct effects to natural resources as well as through influence on the location and form of future urban growth. These environmental effects have the potential to be as revolutionary as those that accompanied the transition to electrical power itself.

Despite these implications, the environmental effects of infrastructure transitions remain largely unexamined *ex ante*, and thus, the direct and indirect environmental implications of a low-carbon energy paradigm are still poorly defined. While decarbonizing the electric power sector necessitates a transition from the existing high-carbon system, a spatial spectrum of divergent potential low-carbon energy solutions is inherently feasible given that renewable resources such as solar and wind are at once both ubiquitous across the landscape and highly concentrated in specific areas. At one end of the spectrum, it is possible to construct large (utility-scale) renewable energy generators following the existing centralized electric power paradigm. At the other end, the potential exists for a fundamentally different structure involving small-scale, distributed renewable energy generators situated at or close to points of consumption. It is currently unclear what potential changes in the morphology of the electrical power system may occur as society increasingly transitions to generation from renewable resources, and what environmental and urban development consequences may result. The research presented in this dissertation collectively contributes innovative approaches to reducing this uncertainty before widespread energy infrastructure transitions occur. These approaches involve looking backwards to conceptualize the relationships between energy, environment, and urban development through time—then projecting forward with novel geospatial methods to forecast potential direct environmental resource impacts and indirect urban development effects of various future low-carbon energy system scenarios.

Throughout history, shifting spatial opportunities and constraints associated with past primary energy source and infrastructure system transitions have resulted in significant and varying patterns of direct environmental effects, as well as changing spatial locations and configurations of urban development. The impending transition to low-carbon energy resources can also be expected to induce such changes. In this work, the potential direct air pollution, water consumption, and land use conversion effects of six future regional energy system scenarios involving centralized and decentralized low-carbon generation sources are temporally and spatially projected. It is discovered that by 2030, carbon reduction scenarios generally confer co-benefits in terms of reduced regional water consumption and pollutant emissions relative to business as usual, but require significantly more land conversion. Furthermore, the magnitude of these effects within individual scenarios shows wide spatial variation across the region. Among the decarbonization scenarios themselves, the region-wide effects vary by as much as 108,000 annual tonnes of air pollution, $145\text{x}10^9$ annual liters of water consumption, and 491,500 cumulative square-hectares of land conversion. Focusing on the indirect environmental effects of a transition, the impacts of a shift to distributed photovoltaic electricity generation on net energy consumption along Sacramento's electrical grid are quantified and the resulting influence on patterns of future urban growth in the city is simulated. Relative to a base growth scenario, a scenario emphasizing distributed rooftop photovoltaic energy generation would have both locally concentrating and regionally dispersing influences on future urban growth and would favor diffuse single land use development. These results suggest that, in particular, there is a trend towards significant environmental consequences from additional future direct and indirect land use associated with a low-carbon energy transition—whether generation sources are implemented at largely centralized, decentralized, or a mix of scales.

Cumulatively, the research presented in this dissertation has significant implications for energy policymaking and the field of environmental planning. Because a transition to low-carbon energy systems presents fundamental choices regarding what resources and generation scales to target, it is critical to consider the ways in which urban development and environmental impacts may change in response to different future energy system scenarios. Understanding the potential for future energy scenarios to result in such effects is critical to making informed assessments of the energy pathways available to society and to avoiding unintended environmental consequences. Moreover, the infrastructure-urban development-environment relationships conceptualized and the approaches presented herein have the potential for widespread application beyond energy systems given that many of the critical infrastructures upon which society depends are networked systems. The ability to forecast change in infrastructure systems and predict impacts before they occur can and should move the practice of environmental planning towards energy-conscious, proactive intervention at local and regional scales in order to avoid unintended environmental consequences of energy infrastructure transitions and associated urban development.

This work is dedicated to my daughter Madeline, my husband Brandon, and the rest of my amazing family. Without your love, support, encouragement, and understanding this accomplishment would never have been possible.

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Chapter 1. Introduction

Of the major infrastructure systems upon which society relies, energy systems have been some of the most influential yet under-recognized drivers of human development and environmental degradation. By 2050, energy consumption is projected to increase by over 65 percent (%) globally while electricity demand is expected to nearly double (Kiesecker & Naugle, 2017). According to the United Nations (2018), 68% of the world's population is expected to be living in urban areas by 2050, an increase from 55% today which will make infrastructure systems all the more critical. At the same time, in the context of the serious climate change challenges facing society today, the energy sector is entering a period of significant transition in primary energy sources, turning from fossil fuels to a variety of renewable and low-carbon resources. Such a transformation carries with it possibilities for social and ecological revolution as astonishing as those stimulated by the first electrical power systems in the nineteenth century (Jiusto, 2009). It will require dramatic changes in the technologies and networks via which we produce and deliver electrical power. And, based on the precedent of historical energy source transitions, these changes can, in turn, be expected to propagate new patterns of environmental impact across the landscape—both through direct effects to natural resources as well as through influence on the location and form of future urban growth. Yet beyond the context of carbon reductions, the direct and indirect environmental implications of a low-carbon energy paradigm are still poorly defined. It is currently unclear what potential changes in the morphology of the electrical power system may occur as society increasingly shifts to generation from renewable resources, and what environmental and urban development consequences may result. With this dissertation, I seek to contribute to such an understanding by first looking backwards to conceptualize the relationships between energy, environment, and urban development through time—then projecting forward with novel geospatial approaches to forecasting potential direct environmental resource and indirect urban development effects of various future low-carbon energy system scenarios.

The infrastructure systems society has developed to harness and deliver energy have profound effects on the environment. Technological systems, particularly networked infrastructure systems like the electrical grid, have long served as humankind's means of adapting to and altering our surroundings (Stine & Tarr, 1998). Such networked infrastructure systems impact the environment directly through their construction and operation, as well as indirectly by influencing resource use and land use patterns. In particular, these infrastructure systems play a significant role in shaping locations and forms of urban development, which is arguably the most extreme type of environmental modification caused by humans (Dale, Efroymson, & Kline, 2011; Melosi, 1990; Monstadt, 2009). According to Pasqualetti (2013, p. 11), "so dominating a role does energy play in the lives we lead and the land we use that its impacts are everywhere." Similarly, Ferrey (2004) proclaims that electric power is the development fluid of modern society. By extension, as Monstadt (2009) argues, the ways in which we develop, govern, and renew infrastructure systems such as the electric grid will largely determine the impact of society on nature.

Throughout history, the United States has appropriated one major energy resource after the next, and currently is in the midst of a burgeoning transition to renewable sources—a shift involving new technologies, energy infrastructure changes, and environmental implications. Historically, America has transitioned through various energy sources—from wood and water; to coal; to oil and natural gas—and come to rely on electricity as a secondary form of power. The resulting electrical grid as we know it today, an infrastructure system with over 17,000 central station power plants tied to load centers via a ubiquitous web of hundreds of thousands of miles of transmission and distribution lines (Pasqualetti, 2013), is largely predicated on technology designed for the generation, transmission, and consumption of electric energy produced from fossil fuel resources. Yet driven by climate change concerns and efforts to achieve greater environmental sustainability, a novel energy paradigm is emerging with a focus on producing electricity from low-carbon sources. As of 2017, for example, 40 states and territories of the United States have mandatory or voluntary goals to increase the amount of electricity generated from renewable resources (Barbose, 2017; Durkay, 2017), along with net metering laws, interconnection guidelines, and renewable energy tariffs to support these objectives (Elkind, 2009; Kelley, 2008).

While decarbonizing the electric power sector necessitates a transition from the existing high-carbon system, the nature of renewable resources makes a spatial spectrum of divergent potential low-carbon energy solutions inherently feasible. Renewable resources such as solar and wind are at once both ubiquitous across the landscape and highly concentrated in specific areas. Thus, at one end of the spectrum, it is possible to construct large (utility-scale) renewable energy generators to capture concentrated renewable resources and transmit power long distances to consumers following the existing centralized electric power paradigm. Conversely, at the other end of the spectrum, the potential exists for a fundamentally different electricity supply structure involving numerous individual small-scale, distributed renewable energy generators situated at or close to points of consumption (Alanne & Saari, 2006; Burton & Hubacek, 2007; Wolsink, 2012). Neither scale of renewable energy generation seems wholly inevitable; some scholars suggest that massive, centralized power systems are too embedded to displace, while others argue that trends in renewable energy technologies and cultural norms foreshadow a shift towards more decentralized power supply (Jiusto, 2009; Bridge et al., 2013; Carley & Andrews, 2012). There is also legitimate normative debate about the social, cultural, and environmental merits of centralized verses decentralized renewable energy futures (Bridge, Bouzarovski, Bradshaw, & Eyre, 2013; Lovins, 1976). While the results of this dissertation may inform such a debate, the debate itself is not my focus.

Notwithstanding beneficial reductions in global carbon emissions, the broader environmental effects of any low-carbon energy transition, if unrecognized or unchecked, are likely to be as significant as those associated with past energy system shifts from wood to coal and later to widespread electrification. Historically, society has perceived each newly-appropriated energy resource as having the potential to effect utopian societal change by providing better, cheaper, infinitely more abundant energy (Melosi, 1985; J. C. Williams, 1997). Renewable resources are today regarded much the same way. However, energy systems produce a large number of direct environmental impacts affecting air, land, and water, among other resources (Sovacool, 2014). The true environmental cost of the electrical network, moreover, are cascading—extending well beyond the direct resource effects of just its construction and operation—given that it is inter-connected to many other critical infrastructures. Critical infrastructure systems such as water, sewage, transportation, and telecommunications are all dependent on and supported by electrical power. Thus, changes to the resources, technologies, and infrastructure associated with the electrical grid will affect other infrastructure systems and in turn influence the environmental impacts of those systems. Moreover, a low-carbon energy future will require significant changes in the technologies and networks via which we produce and deliver electrical power—a fundamental infrastructure transition that will undoubtedly drive landscape transformation in the twenty-first century (Dale et al., 2011; Nadaï & van der Horst, 2010). Stremke and van den Dobbelsteen (2013, p. 3), for example, observe that on par with the introduction of the automobile, the emerging transition to renewable energy resources is “another land use that will affect the spatial organization of the larger physical environment across the world.”

Despite the notion that development and renewal of infrastructure systems will profoundly influence environmental change, the potential environmental effects of infrastructure transitions remain largely unexamined *ex ante*. As a result, intentional modifications of infrastructure systems often produce unintended environmental consequences when technologies believed to be relatively benign are deployed en mass (Kranzberg, 1995; Melosi, 1990). This problem suggests a critical need to explore more deeply the potential environmental implications of a low-carbon energy transition prior to its implementation. However, little contemporary work on low-carbon energy transitions focuses on the potential environmental and urban development consequences of such infrastructure change, much less in a spatial context or across geographic scales. In an analysis of energy-related research including over 4,000 articles published in the top three energy journals between 1999 and 2013, (Sovacool, 2014) found that only 3.5% of articles mentioned energy-related environmental impacts (other than climate change), only 1.1% of articles included discussion relating to geographic scale and/or space, and only 0.6% of authors reported disciplinary training in spatial sciences, land use planning, or geography. Moreover, (Bridge et al., 2013) suggest that while the temporal concept of ‘transition’ as change over time is often a focus of research on shifts to low-carbon energy systems, the spatial concept of ‘transition’ in terms of change in the morphology of energy systems and the organization of society is generally overlooked. Similarly, (Pasqualetti & Brown, 2014) argue that while much research has focused on energy policy intervention to mitigate climate change, the environmental externalities of changes in energy systems can vary widely over space, and much more work is needed to better understand the spatial consequences of such energy policies on society and the environment.

At a fundamental level, the research presented in the following three chapters collectively contributes innovative approaches to understanding the potential environmental implications of policies intended to transition society’s energy infrastructure to low-carbon energy sources—before such transitions occur. This research includes looking to the past to understand the future by analyzing historical energy source, environment, and urban development relationships in order to better conceptualize the interrelated effects of future transitions associated with decarbonizing society’s energy infrastructure. It involves forecasting potential environmental implications at both ends of the spatial spectrum of potential solutions (e.g. centralized vs. decentralized low-carbon energy production), as well as in terms of direct and indirect impacts (e.g. direct effects on natural resources and indirect influences on the location and form of future urban growth). I present a summary of each chapter and highlight my findings below.

Chapter 2. Energy’s Influence on Urban Development and the Environment

In Chapter 2, I trace America’s historical energy transitions over time with a focus on the urban development and environmental implications of various dominant energy sources, and the associated technological systems used to produce and deliver power from those sources. Through this work, the effects of shifting energy opportunities and constraints on both the natural and the built environment become apparent across many spatial scales. The transition from one primary energy source to another over time, along with new associated technologies and changing infrastructure networks to produce and deliver power, have resulted in varying forms and locations of environmental degradation. Moreover, the spatial patterns of urban development in America—both the location and form—can often be traced back and linked to the availability and development of energy resources. In fact, I find that historic energy source transitions have supported urban growth in changing locations and facilitated both concentration and diffusion in city form. Despite these implications, I contend the role of energy as a force shaping urbanization has been marginalized in existing theories of urban development, possibly due to a focus on the role of transportation, which itself is an infrastructure system influenced by energy sources. In the final part of this chapter, I discuss the potential for a new transition from fossil fuels to renewable primary energy sources. Acknowledging that uncertainty remains over what resources and generation scale a future low-carbon energy system may involve, historical precedent suggests that any such transition is likely to alter the direct environmental effects of our energy system as well as present new choices about where and how to urbanize. Given the potentially significant ramifications of such change, I conclude that greater understanding of the potential for future energy scenarios to influence both patterns of urban development and direct impacts to natural resources is critical to making informed assessments of the future energy pathways available to society while avoiding unintended environmental consequences.

Chapter 3. Regional land, water, and air pollutant emission effects of low-carbon power system scenarios for western North America

Heeding the second chapter's conclusion that informed energy and environmental planning will require foresight into the nature and distribution of potential direct impacts to natural resources under various future low-carbon energy system scenarios, in Chapter 3, I present a novel simulation and assessment approach to serve this purpose. Using this approach, I examine the spatial and temporal distribution of air pollution, water consumption, and land use conversion directly associated with the future operation and expansion of the electrical grid in North America's Western Electricity Coordinating Council (WECC) region under six different low-carbon energy system scenarios and a business-as-usual (BAU) scenario. I find that by 2030, the carbon reduction scenarios generally confer co-benefits in terms of reduced WECC-wide water consumption and pollutant emissions relative to BAU, but require significantly more land conversion. Furthermore, these effects vary across the decarbonization scenarios themselves by as much as 108,000 annual tonnes of air pollution, $145\text{x}10^9$ annual liters of water consumption, and 491,500 cumulative square-hectares of land conversion. I also find significant spatial variation in the level of these impacts both within and among scenarios. Overall, I conclude that a scenario encouraging increased distributed renewable energy generation minimizes the regional magnitude of these impacts while achieving the desired carbon reduction goals. While decarbonizing the electrical sector is essential to mitigating global climate change impacts, these results reveal that the specific mechanisms employed to achieve carbon reductions can greatly influence the location and magnitude of direct environmental effects at local levels. I caution that failure to take such localized environmental implications into consideration is likely to lead to energy-climate policymaking that undermines equally important environmental policy goals, such as the preservation of water resources in the arid west in the face of climate change. Instead, I argue that an approach of integrating multi-resource environmental assessments into energy scenario analysis can aid policymakers and planners in identifying and addressing unnecessary or inequitable direct environmental consequences of energy infrastructure transitions before they occur.

Chapter 4. Solar Sacramento: An approach to measuring the effect of distributed photovoltaic (PV) energy generation on the spatial supply-demand balance along the electrical grid and simulating the resulting influence on future urban development

Like Chapter 3, the fourth chapter presents a novel method of conceptualizing the potential environmental implications of a low-carbon energy transition, yet from an opposite, but equally environmentally significant, perspective. In this chapter, I present an approach to quantifying the effect of a shift to distributed photovoltaic electricity generation on net energy consumption along the electrical grid in the City of Sacramento, California and simulating the resulting influence on the pattern and form of the city's future urban growth. Although, I conclude in Chapter 3 that a scenario incorporating distributed renewable energy generation may minimize the direct air, water, and land use conversion impacts of a low-carbon energy transition, these are not the only potential environmental effects of such a transition. In contrast to and expanding upon the analysis in Chapter 3, the approach I present in Chapter 4 is focused on the indirect environmental effects of a transition to distributed renewable energy generation via its potential to shift patterns of urban development. I find that the spatial balance of supply relative to consumption varies across the electrical network, and network elements from the meter-level up through certain distribution feeders can exhibit renewable supply that exceeds consumption. Furthermore, I find that relative to a base growth scenario, a scenario emphasizing distributed rooftop PV integration would have both locally concentrating and regionally dispersing influences on future urban growth and would result in less mixed land uses in favor of diffuse single land use development. These results suggest that there is a potential for a transition to distributed low-carbon energy systems to conflict with other objectives of sustainable urban development such as increasing mixed land use and urban concentration. Therefore, I conclude that proactive energy and environmental planning will require not only consideration of the direct natural resource impacts of any potential low-carbon energy transition, but also such approaches to assess the complex urban development effects so that decision makers can consider the implications in the context of other urban sustainability objectives.

Cumulatively, the research presented in this dissertation has significant implications for energy policymaking and the field of environmental planning. Climate change is the central environmental challenge facing humanity today and addressing this problem will require tremendous transformations in how society generates, transmits, and consumes energy. Because transition to low-carbon energy systems presents fundamental choices regarding what resources and generation scales to target, it is critical to consider the ways in which urban development and environmental impacts may change in response to different future energy system scenarios. Such forward thinking will aid planners and policymakers in holistically evaluating the choices and pathways available to society and in avoiding unintended conflicts between energy development and the environment before they occur. This is a fundamental paradigm shift for the practice of environmental planning. Historically, environmental planning has been rooted in adaptation rather than prevention of environmental consequences associated with changes in infrastructure and patterns of development. The approaches presented herein provide novel methods to move practice away from adaptation and towards prevention. Moreover, while this dissertation focuses on transitions in energy infrastructure in the context of climate change, given the inter-connected nature of this system with other critical infrastructures, the effects are likely to be cascading. Likewise, the infrastructure-urban development-environment relationships conceptualized and the approaches presented herein have the potential for widespread application beyond energy systems given that many of the critical infrastructures upon which society depends are also networked systems. The ability to forecast change in infrastructure systems and predict impacts before they occur can and should inform proactive planning, design, and policymaking that move the practice of environmental planning from response to avoidance of unintended environmental consequences.

Chapter 2. Energy's Influence on Urban Development and the Environment

I. Introduction

The spatial patterns of the built environment in America—both in terms of location and form—can often be traced back and linked in part to the availability of energy resources and the infrastructures used to harness and distribute their power. The process by which cities establish, expand, and change is inextricably tied to the resources available to support and facilitate urban development. As Tilly (1974) observed in *Metropolis as Ecosystem*, "the metropolis is a dependent ecosystem… all ecosystems require a continuous supply of energy to power their activities." Since the nineteenth century, the United States has transitioned through various dominant primary energy sources—from wood and water, to coal, to oil and natural gas—and come to rely on secondary forms of power, namely electricity. While these new dominant sources of energy did not deterministically prescribe the spatial patterns of industry, people, and the built environment, nor were they the only influence on such patterns, novel locational opportunities arose with each source transition (and related energy technologies) enabling new cultural decisions about where and how to urbanize. In a purposeful oversimplification, Dale et al. (2011, p. 758) suggest "where cheap, convenient energy is provided, people settle; towns spring up; and land uses change for the long term." In fact, as Rosa, Machlis, & Keating (1988) argue, the availability of energy, the technical means for converting energy into usable forms, and the ultimate uses of energy condition life-styles, broad patterns of communication and interaction, collective activities, and key features of social structure. Moreover, the dominant energy sources used by society and the means by which they are extracted, converted to power, and transmitted have direct impacts on the environment. The urbanization facilitated by energy consumption has significant environmental effects as well. Today, the potential for a new transition in predominant primary energy sources from fossil fuels to renewable resources has emerged. In this context, the nature of some renewables—at once ubiquitous across the landscape and highly concentrated in specific locations—presents new choices for generating power in centralized and/or decentralized locations. While uncertainty remains over the exact nature of a low-carbon energy future in America, history suggests that a transition in the dominant energy sources used to power the country is likely to change constraints on the locations and form of urban development, as well as alter the direct and indirect environmental effects of our energy system.

This chapter traces America's historical energy transitions over time with a focus on the urban development and environmental implications of various dominant energy sources and the associated technological systems used to produce and deliver power from those sources. America's energy history includes three major periods of dominant energy sources and associated technologies: wood, water, and wind prior to the nineteenth century; coal during the nineteenth century; and oil, natural gas, and electricity in the twentieth century. In tracing the these periods over the course of this chapter, I demonstrate that the historical transitions between these sources have influenced changes in the location, growth, and form of settlements as well as shifted the type and magnitude of environmental effects associated with the energy system. I conclude the chapter by discussing the drivers of and potential for an impending primary energy transition from fossil fuels to renewable resources and considering how such a change might influence future patterns of urban development and environmental impacts.

While transportation is often cited as central to the study of energy, urban development, and environmental impact, transportation is not the focus of this work. There is already an extensive literature on topic of transportation and urban development (e.g. Doherty, Nakanishi, Bai, & Meyers, 2009; Muller, 2004; Warner, 1962). Moreover, some scholars (e.g. Rose & Clark, 1979; Viehe, 1981, 1991) suggest that the focus on transportation as a primary driver of locations and forms of urban growth may undermine our understanding of other influencing factors, such as energy resources themselves. Viehe (1981), for example, argues that the transportation thesis has for too long dominated thinking regarding suburbanization. Rose and Clark (1979) lament that while urban scholars have produced many insightful studies about how transportation has influenced urbanization, they have focused little on the role of new energy technologies in reshaping cities.[1] In fact, Melosi and Pratt (2007) suggest that new sources of energy, along with the technologies developed to convert those sources into power, were actually the catalysts that shaped the transportation revolutions often attributed with transforming the built environment. Wood, and later coal, fueled the trains that transformed the American landscape; then oil fueled the cars and planes that extended the transformation. As Platt (1987) proclaims the study of energy sources as a separate influence has not been clearly or adequately considered in our quest to understand the process of urban development.

The ways in which societies secure energy and transform it to do useful work influence their geographic structure at many scales (Bridge et al., 2013; Jiusto, 2009; Melosi, 1990; Owens, 1979, 1986; Pratt, Melosi, & Brosnan, 2014; Rose & Clark, 1979; Rosenberg, 1998). Geographer Owens (1981, 1986) argues that at all levels of spatial resolution—from local to regional scale—energy systems influence urban location and spatial structure, but she concludes the relationship is complex, often indirect, and reciprocal. This complexity is reinforced by the embedded nature of the relationship in complementary and indirectly linked cycles of innovation in transportation, industry, technology, agriculture, communication, and governance (Jiusto, 2009), as well as shifts in social and environmental conditions. Relevant energy factors that can influence the location and growth of settlements and the density and degree of interspersion in urban form[2] include: the location and abundance of energy resources; the nature of the resources in terms of transportability and energy density; the technologies available to convert energy sources into useful power; the economic and environmental costs of different energy sources and associated power generation technologies; and the regional economic benefits of energy production (Melosi & Pratt, 2007; Owens, 1979, 1986; Platt, 1987; Pratt et al., 2014). These energy factors may have reinforcing or conflicting implications for urban location and spatial structure, and urbanization processes are also subject to external technological, social, and environmental

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[1] In his classic work, *Streetcar Suburbs*, Warner (1962) postulates that the suburbanization of Boston was induced

[2] The term "urban form" generally refers to the shape, size, density, and intermix of industrial, commercial, and residential land uses in a built environment. (Doherty, Nakanishi, Bai, & Meyers (2009) provide detailed definitions of these components and note that the merits and drawbacks of two primary urban forms, dispersed/sprawling and compact/dense cities, have been debated since the early nineteenth century. Herein, I use urban form to refer to the density and intermix of land uses in the built environment. Following Owens (1986), I use the terms urban form and spatial structure interchangeably. I use the term urban development to refer to both the location and form of urbanization.

influences. Moreover, Owens (1981; 1979) points out that the location, growth, and form of urban areas can themselves influence energy demand which in turn influences energy availability, the development of new technologies for energy production and consumption, and the search for new sources of energy. Figure 1 conceptually represents this complex and reciprocal relationship.

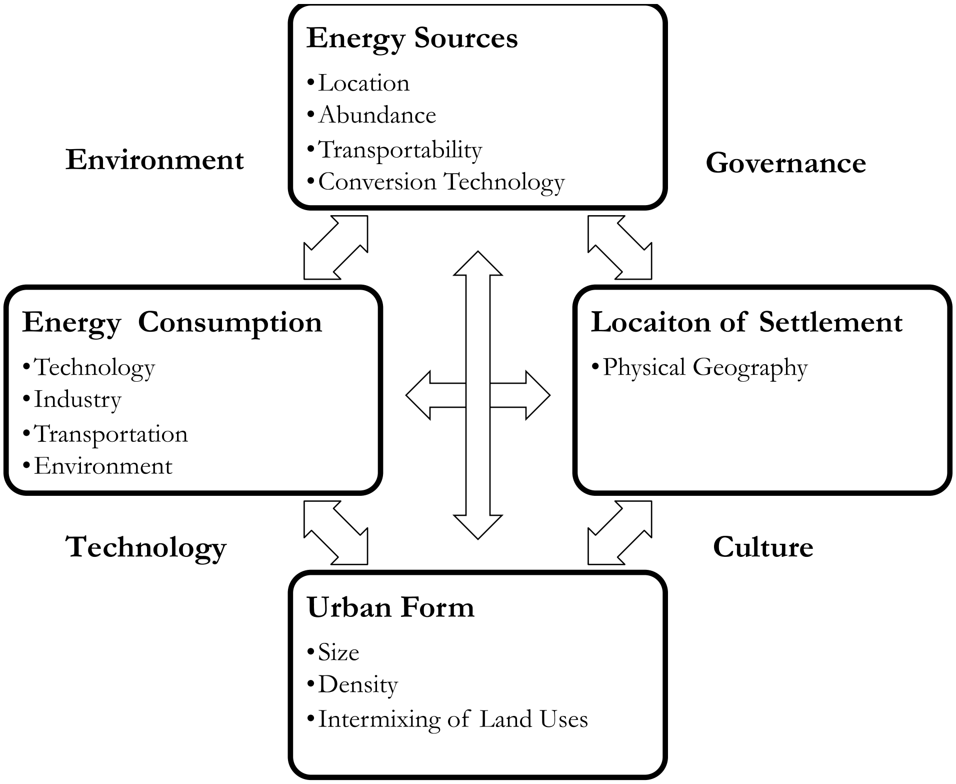

Figure 1. Simple conceptual model of the reciprocal relationships between energy sources, urban development (location and form), and energy consumption.

Over the past three centuries, the United States has seen a few major shifts in the dominant fuels and energy conversion technologies used to supply its power, and according to historians Melosi and Pratt (2007), a key challenge in urban and environmental history is to identify and analyze the central effects of such energy transitions on the evolution of cites. Owens (1986) suggests that while energy transitions do not deterministically prescribe changes in the built environment, as a crucial permitting factor in the process of urbanization, energy has certainly exerted a profound influence on the location and form of urban development through time. Yet, in their book *Energy Capitals*, Pratt et al. (2014) contend that while the strong, complex connections at the intersection of energy development, urban growth, and environmental impacts are intuitively obvious, they are largely missing from existing historical literature, perhaps because they are too deeply embedded to be easily analyzed. Historically, new dominant primary energy sources have attracted industry and to locations where they are concentrated or easily delivered (Viehe, 1981), given birth to unique energy-related enterprises and industries (Platt, 1987), facilitated changing modes of transportation (Melosi & Pratt, 2007), and permitted greater locational flexibility and growth in industrial development (Miller, 1987). These effects in turn led to new settlements as well as growth of existing cities through increased economic activity, which attracted population (Burchell & Listokin, 1982) at the same time that the new energy sources and associated technologies modified constraints on urban form.

By permitting changing locations and forms of urban development and directly through their construction and operation, energy infrastructure systems can also profoundly impact the natural environment. According to Pasqualetti (2013, p. 11), "so dominating a role does energy play in the lives we lead and the land we use that its impacts are everywhere." Direct environmental impacts caused by energy systems vary based on factors such as the energy resource being harvested, the infrastructure used to convert that source to power, and the amount of consumption. Impacts can include: land degradation from extraction, transportation, conversion of fuels, and generation and transmission of power; extensive use of water; air pollution from burning of certain fuels; waste creation; and other effects. This chapter ventures to capture (but not extensively discuss) the types of direct environmental impacts associated with different energy resources throughout American history as a means of demonstrating that the broader environmental effects of energy production and consumption have changed along with these changing energy sources. Urban areas themselves are also major modifiers of the earth's environment (Melosi, 1990). Urban development requires large amounts of land, water, air, and resources to sustain human populations. Urbanization can affect habitat (by consuming land for the built environment), hydraulics (by extensive water use, removing filtering capacity of soils, filling wetlands, and channeling precipitation into watercourses), atmosphere (by increasing airborne pollutants and creating "heat islands"), nutrient cycling (by creating huge volumes of waste products that require complex disposal mechanisms), and disrupt other environmental factors (Pratt et al., 2014). Over time, the production and use of energy have facilitated this process of environmental change through urban development by removing constraints on where urbanization occurs and the spatial structure it takes.

Acknowledging the relationships between energy, urban development, and the environment, the location and form of urban growth in America, as well as the environmental effects of our energy system, will likely continue to respond to future energy transitions. Today, in the context of anthropogenic contributions to climate change, concepts of energy security, promotion of sustainability, and advances in renewable electricity generation technologies, the potential for another energy transition from fossil fuel to renewable resources has emerged. Renewable resources such a wind and solar are simultaneously ubiquitous across the landscape and more concentrated in specific locations. This duality presents new choices for generating power in a variety of configurations ranging from highly centralized to highly decentralized systems. While it is unclear exactly what resources and generation scale a future low-carbon energy system may involve, it is nevertheless critical to consider the ways in which urban development and environmental impacts might change in response to further transition in the energy system. Such forward thinking will aid planners and policymakers in evaluating the choices and pathways available to society and in mitigating any undesirable consequences.

II. American Energy Sources, Urban Development, and Associated Environmental Implications Through Time

This historical discussion is structured around three distinct periods in American energy identified by energy geographer Martin Pasqualetti (2013): the organic, mineral, and electric energy economies, as well as three generally corresponding periods of American urbanization as outlined by urban historian Martin Melosi (1990): the pre-industrial city (prior to 1840), the industrial city (1840-1920), and the metropolitan era (post 1920). Americans have exploited various forms of energy over time including wood, water, and wind prior to the nineteenth century, coal during the nineteenth century, and oil, natural gas, and electricity in the twentieth century (Figure 2). While the change from one set of dominant energy sources to another was neither immediate nor absolute (Melosi, 1985), the broad transitions between these sources facilitated shifts in locations of urban growth and characteristics of urban form, as well as changes in the environmental effects of the energy system.

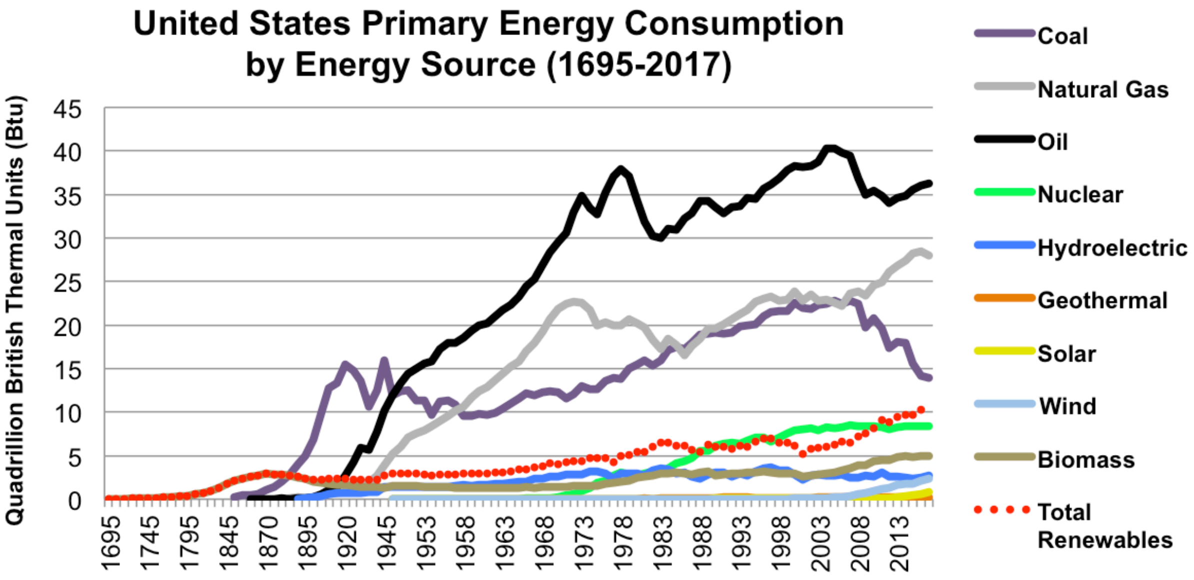

Figure 2. Change in primary energy source consumption through time in the United States. Note that through 1945 "biomass" data are for fuel wood only. Beginning in 1949, biomass data are for wood and wood-derived fuels. Note there is also an absence of waterpower data prior to conventional hydroelectric use in 1890. (Source data from United States (U.S.) Energy Information Administration, 2018a, 2018b).

While the history presented here focuses on the United States, energy resources have played a role in shaping urban development in other locations as well. For example, waterpower formed the basis for substantial pre-industrial development in much of Europe and by the eighteenth century, population was concentrated along its waterways and urban expansion was limited given that the power produced by a watermill could not be efficiently transported (Cook, 1976). In nineteenth-century Europe, the geographical pattern of industrialization and urbanization closely coincided with the geological distribution of coal beneath the ground[3] (Bridge et al., 2013; Hall, 2002). Nye (1994) contrasts the energy resources that facilitated the industrialization of Europe with those in the U.S., and the distinctive urban spatial structure they produced. He argues that coal- and steam-power-driven industrialization concentrated factories, people, and urban growth in European cities, while America relied on waterpower for its early industrialization resulting in factories, clusters of workers, and small communities distributed throughout the countryside (Nye, 1994). Beyond Europe, Pasqualetti and Brown (2014) suggest that energy has provided both the seed and the sustenance of cities as diverse as Baku, Kuwait City, Abu Dhabi, Singapore, and Kogalym.

The following sub-sections describe the energy resources, urban development, and associated environmental implications during the organic, mineral, and electric energy periods in the United States. The chapter concludes with a discussion of energy and urbanization between the 1960s and present day.

A. Organic Energy Sources and the Pre-industrial City (Prior to 1840)

In America, water, wood, and to a lesser extent, wind were the prime energy resources of the European colonial, pre-industrial era (Jackson, 1985; Melosi, 1985), and the availability of these resources influenced early patterns of European settlement and industry (Burchell & Listokin, 1982; Dale et al., 2011; Nye, 1990, 1994). While European governments took different approaches to their colonizing efforts (M. E. Ackermann, 2008), the first English European settlements were located along the Atlantic Coast and fostered a process of town diffusion and succession of the urban frontier into the continental interior and towards the West.[4] During this period, cities were compact in form (rarely extending further than two miles from their center) with high population densities, mixed patterns of land use, and little separation between the workplace and domicile (Miller, 1987; Tarr, 1984). These characteristics can, in part, be attributed to the organic (wood, water, wind) sources that constituted much of the energy base, coupled with the fact that walking and/or animal-drawn transportation were the primary methods of intra-city travel (Burchell & Listokin, 1982; Miller, 1987; Pratt et al., 2014; Tarr, 1984). As European settlement increased, perceived abundance of these energy sources and the belief in manifest destiny led to environmental impacts associated with their extraction and consumption.

A.1. Water

The placement of the first American settlements, be they of English, French, or Spanish patronage, was often dictated by the presence of a water body that could be used for power and transport (Burchell & Listokin 1982). At the start of the colonial period in the early seventeenth century, settlers arriving from Europe first built water-powered mills to process grain and timber

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[3] Patrick Geddes identified and illustrated the spatial correlation between coal deposits and regional clusters of cities in England (Hall, 2002). He saw the combination of organism, function, and environment (folk, work, place) as a key to understanding human settlement and civilization and developed the "valley section" as a conceptual model demonstrating how regional physical geographies (such as coal deposits) support occupations/economic development that in turn determine patterns of human settlement (Thompson, 2004).

[4] In contrast, the first French colonies were trading posts in Newfoundland and settlements in Quebec, Montreal, and later Louisiana, while the first Spanish settlements were in Florida, New Mexico, and across Texas and California (M. E. Ackermann, 2008).

(Sachs, 2015). In the West, Spanish setters located near flowing streams and built small horizontal gristmills alongside troughs built to divert water; they increased the number of gristmills along such troughs in conjunction with population and economic needs (Gritzner, 1974). Similarly, water-powered mills became the basis for numerous small mill towns across mid-Atlantic states including New England, Maine, and New York (Nye, 1994; Tarr, 1984). In the Northeast in particular, the use of water-powered mills for local grain and timber gave way to larger scale water-powered commodity production that supported economic and physical growth of settlements. For instance, McKelvey (1945, p. 3) describes early Rochester, New York as the "Water-Power City" proclaiming "if ever a town's site was prepared and its character largely determined by the varied actions of an ever-abundant water supply, it was the Rochester of a hundred years ago." Born in 1812 as a hamlet clustered around a few primitive lumber and grist mills along the lower Genesee River, Rochester became "America's first boom town" sprawling astride the river whose falls turned a hundred millstones (McKelvey, 1945). By the 1820s, a new inland urban frontier had emerged along eastern waterways that could provide power and serve as a means of transport, illustrating the centrality of waterpower in early settlement of this part of the country (Burchell & Listokin, 1982; Nye, 1994; Tarr, 1984). Unlike in the Northeast, California historian J. C. Williams (1997) asserts that the mountain location and character of California rivers largely prohibited pre-industrial, water-powered boomtown communities like those in the East.

The use of water as a power source also dictated the potential location and size of early industrial development. In addition to timber and grain processing, by the eighteenth century watermills commonly powered paper, textile, and dye processes (Sachs, 2015). Slater Mill, which is recognized as the birthplace of the U.S. factory system, was located along the Blackstone River in Rhode Island in 1793 (Miller, 1987; Tarr, 1984). By the 1820s, textile factories powered by watermills in Lowell, Massachusetts employed thousands of young women from parts of the New England (Sachs, 2015). The early reliance of such industry on waterpower dispersed these factories into the hinterlands along isolated waterpower sites, at the periphery of cities that developed adjacent to rapidly running water, or along specifically built races through which water was run to power machinery (Miller, 1987; Nye, 1994). Moreover, the reliance on waterpower influenced factory size, which generally correlated with the amount of flow along, and thus power produced by, the adjacent waterway. On a broader scale, waterpower also provided some constraint on industrial expansion given the power produced by a watermill could not be transported very far away from the mill (Cook, 1976).

A.2. Wood

Wood was almost certainly the first primary energy source used by humans, and for 250 years after settlers colonized America, fuel wood remained the principle source of inanimate energy (Cook, 1976). In addition to those relying on flowing waterpower, pre-industrial cities located and expanded where there were sufficient timber resources (Dale et al., 2011; Melosi, 1985). Forests served as a source of fuel wood for home heating, early industrial processes, and transportation. Clearing land of trees also created space for expansion of agricultural and urban development. An established wood-based energy system developed in early America with associated technologies (e.g. fireplaces and steam boilers adapted for wood) as well as supporting economic institutions (e.g. professions and markets) (Melosi, 1985; Whitney, 1994).

Large wood-producing areas attracted colonial settlement and supported urban expansion in the pre-industrial era. Emerson, in 1846 (as cited in Whitney, 1994), described energy production as the most "extensive and important" use of America's forests for well over 200 years, and, until the late 1800s, more wood was used for fuel than construction. The rich forest resources of the Northeast supported early settlements as they transitioned to larger cities. Dense Pennsylvania forests, for example, provided the settlements at Philadelphia and nearby Wilmington, Delaware with a significant supply of fuel for iron production, and between 1750-1800, Philadelphia reigned as the largest city in North America (Matlack, 1997). Towns such as Chester, Hopewell, and Hibernia, Pennsylvania, and Iron Hill, Delaware also relied on wood burning to make charcoal—the fuel that drove the burgeoning iron-making industry which supported their existence (Matlack, 1997; Sachs, 2015). According to Matlack (1997), the bulk of wood and the poor condition of colonial roads made it unprofitable to haul timber more than 40-50 kilometers (km), so wood for settlements generally came from within a 50 km radius.

Even as setters ventured west to frontier prairies, wood remained a crucial fuel for settlement. In *Nature's Metropolis,* his seminal work on the linkages between Chicago and its hinterlands, Cronon (1991, p. 153) notes that timber heated homes, cooked meals, and supplied the energy that ran steam engines, thus "lacking a ready supply of wood, no town could come into being or aspire to become a metropolis." Early settlers in the Chicago area "located their farms near watercourses, which flowed like wooded ribbons through otherwise treeless landscapes" (Cronon, 1991, p. 101) and while farms eventually fanned out from these woody areas, they continued to rely on them for lumber and fuel. Eventually, the internal and economic growth of the city replaced the settlement of the prairie as the driving force behind timber demand and the minimal wood sources in the grasslands and prairies could no longer sustain the region (Cronon, 1991). Instead, Lake Michigan provided the growing city with access to the dense forest resources 100 miles to the north in Wisconsin and Michigan. Chicago's growth in the nineteenth century was predicated in large part on this natural capital from a region well beyond its borders (Cronon, 1991). Further south, during the mid-1830s, Houston, Texas was founded as a lumber town situated between rich forests to its north and east (Platt, 1984). When local supplies of timber diminished by the 1870s, the city built railroad lines deeper and deeper into the forests to produce an adequate supply of fuel for continued growth (Platt, 1984).

Accessibility to wood fuel was also a major factor influencing the location of early transportation infrastructure, which in turn attracted and supported urban development. Melosi (1985, p. 22) argues that "wood and the steam engine pioneered the earliest large-scale transportation systems in the [United States]." The steamboat and train locomotive were the primary means of inland transportation from the early to mid-nineteenth century, and until about 1875, most steam engines in North America ran on wood (Cook, 1976). Accessibility to timber was a major factor in the location of transportation routes both because the weight and bulk of the fuel necessitated frequent refueling of steam engines (Melosi, 1985) and because, as the basis of the energy economy, wood was a major commodity to be transported around the nation. Cronon (1991), for instance, describes how railroads extended their lines into southern forests as wood supplies in the Northeast and Great Lakes regions diminished.

A.3. Wind

In addition to water and wood, wind power played a role in opening the great plains to development with hundreds of thousands of windmills eventually dotting the central part of the country (Righter, 1996). Settlers relied on power from windmills when other sources of power were not available and where winds blew with some consistency (Cook, 1976). Such windmills were commonly used to pump water to an elevated tank, storing it as potential energy, to be released to generate power when necessary (Cook, 1976). According to Pasqualetti (2013, p. 15), windmills "quickly became beacons of civilization and hope to farmers across the vast lands between the Mississippi and the Rockies…and they played a critical role in opening the grasslands to permanent habitation."

A.4. Environmental Implications of the Organic Energy Economy

The perceived abundance of energy sources and their driving role in facilitating the location, power, and expansion of settlements precluded attention to the direct environmental consequences of their use and of the indirect consequences of the development they influenced (Melosi, 1985). According to Marx (1991), the dominant American ideology of space derived from initial European impressions of North America framed the continent as a vast, unbounded expanse of potentially valuable, untapped resources. This utilitarian vision of North America led to a view of nature as a "howling wilderness" to be discovered, subdued, and commodified by arriving Europeans (Marx, 1991).[5] By the 1830s the primary "utilitarian" origin story was reframed as "progress" and provided ideological support for the "virtually preordained" consumption of natural resources and conquest of space from the eastern established built environment westward, under the belief that this was America's manifest destiny (Marx, 1991). Nature, in this paradigm, was viewed as a storehouse of resources to be "developed" to satisfy the increasing demand and progress of humans (Devall, 1980).

The forests of America seemed to offer an unending source of fuel for home heating, industry, and transportation, and wasteful consumptive practices led to environmental degradation (Melosi, 1985). As eastern settlements grew, forests receded and local shortages led to increased timber costs. Instead of cultivating this renewable resource in nearby hinterlands, Americans consumed new forest tracts expanding the urban frontier into the continental interior (Matlack, 1997; Melosi, 1985). Whitney (1994, p. 210) quotes botanical explorer Peter Kalm as early as the mid-eighteenth century expressing concern over America's forests being "squandered away in immense quantities day and night all the winter…for fuel." Similarly, Matlack (1997) notes that by 1775 the Philadelphia area was bare of trees, and by 1800, little forest remained in the hinterlands of Wilmington, Delaware. He attributes this largely to the demand for fuel, suggesting clearance for cultivation was more or less restricted to level land, but all forestlands were vulnerable to fuel-wood gathering and those in the northeast were severely affected. The clear-cutting of forestlands contributed to environmental problems including erosion, flooding, poor soil fertility, and altered fire regimes (Cronon, 1991; Pasqualetti, 2013).

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[5] While the dominant ideology was utilitarian, a pastoral origin sentiment saw the New World as the first opportunity to realize the dream of achieving harmony between man and nature through a semi-primitive life that combined the best features of urban and natural environments (Marx, 1991). Thomas Jefferson, in 1780, espoused this pastoral goal of economic sufficiency, not the maximization of production and consumption in the new republic (Marx, 1991). However, this pastoral view remained a minority sentiment.

Waterpower sites became similarly exploited and even wind power development had certain environmental impacts. Watermills required the construction of dams to convey water through their races, and according to Sachs (2015), in areas of high demand, dams could be found every few miles to every few yards. The dams prevented fish populations from moving up river to spawn and caused seasonal flooding of meadows, taking fertile soil out of production (Sachs, 2015). Moreover, the manufacturing mills located at these waterpower sites produced pollutants such as acids, dyes, and sawdust—that were often released directly into rivers (Sachs, 20115). The windmills that supported habitation of the Great Plains were also used for irrigation as they pumped water and released it to generate power, consequently leading to altered hydrology and vegetation shifts from native grasses to invasive species (Pasqualetti, 2013).

While the environmental effects associated with the use of these organic energy sources were significant in their own right, they also foreshadowed the environmental implications of the Nation's growing demand for energy. The effects were to become increasingly pronounced in the era of industrialization and fossil fuels.

B. Fossil Fuels and the Industrial City (1840-1920)

The mid-nineteenth century marked the beginning of a transition from organic, renewable energy sources such as water, wood, and wind, to comparatively non-renewable, mineral energy sources including coal, and later, oil and natural gas. The change from one energy source to another was neither immediate nor absolute—earlier energy resources were supplemented, complemented, and then largely displaced by fossil fuels (Melosi, 1985). In the United States, coal began as an obscure, regional fuel but in the latter decades of the nineteenth century, it rapidly replaced wood and water as it became easier and cheaper to extract and transport (Cook, 1976). By the early-twentieth century, the shift to oil and natural gas was underway. These primary energy source transitions were associated with technological innovations that allowed greater locational flexibility and growth in industrial development, which in turn led to new settlements as well as growth of existing cities through increased economic activity that attracted population (Burchell & Listokin, 1982; Miller, 1987). America's appetite for energy also flourished during this period. With the end of the Mexican American War in 1848, the United States became a continental nation and aspirations for westward expansion and industrialization grew. In 1850, national energy consumption was about 2,000 trillion British Thermal Units, but by 1930, it was ten times that amount, having grown twice as fast as the population (Sachs, 2015).

As Pratt et al. (2014) succinctly put it: fossil fuels helped transform the modern city worldwide, fundamentally changing land-use patterns as urban centers reached out and absorbed the once rural lands surrounding them. Early settlements had been somewhat naturally limited in location and growth by the low energy density[6] of wood fuels and the inability to generate power at any great distance away from flowing water resources. The production and use of concentrated fossil fuel forms of energy greatly relaxed such constraints and facilitated increasing separation of cities from their energy sources. The higher energy densities of fossil fuels allowed these energy resources to be economically transported longer distances (Jones 2010; as cited in Pasqaletti, 2013). Cities rapidly became industrialized, attracting larger populations and growing in physical

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[6] Energy density refers to the amount of energy that can be produced per unit volume of fuel. A fuel with a high energy density requires less volume to produce the same amount of energy as a fuel with a low energy density.

area. As industrial developments grew, they demanded more land, which negated the mixing of residential and industrial land uses once characteristic of many settlements (Burchell & Listokin, 1982). The compact, mixed land use city of the organic energy economy was largely replaced by distended urban areas extending up to 50 square miles with increasingly separate business, residential, and industrial zones (Miller, 1987). American municipalities exerted few institutional controls over their development during this period, leaving private industrial interests to reshape cities and establish new settlements via unregulated, uncoordinated growth (Peterson, 1979). While factories remained in the city, new manufacturing operations also began to settle outside of urban centers near intercity transportation routes creating “satellite cities” (Miller, 1987).

Resource exploitation and environmental degradation dominated development patterns around the country as settlements and growth surrounded easily-accessible fossil fuels and the industries that emerged to extract, process, and transport the energy supplies to users and markets (Dale et al., 2011; Pasqualetti, 2013; Silveira, 2000).

B.1. Coal

While early American settlers had knowledge of European coal mining, coal initially remained an obscure source of energy during the settlement of the United States, but by the 1870s, coal had replaced wood as the primary fuel for steam-powered transportation, and by the 1880s, it had replaced waterpower as an energy source for industrial expansion (Pasqualetti, 2013; Platt, 1987; Melosi, 1985; Tarr & Lamperes, 1981). There was practical reluctance to transition away from organic energy sources such as wood and water because waterpower sites and abundant forest resources were cheap to exploit; clearing land of trees offered space for agricultural and urban development; and an established wood-based economy had developed (Melosi, 1985). Thus, the transition to coal occurred over decades. One factor driving the initial use of coal as a regional fuel was timber shortages. In the last decades of the eighteenth century, the cost of firewood in Philadelphia, for example, was so high that it became economical to import coal from Britain to meet domestic heating needs (Matlack, 1997). According to Melosi (1985), the widespread use of coal as a national energy source was eventually facilitated by a number of primary factors. These included the inability of wood fuels and water power to sustain the growing manufacturing economy; effective transportation of anthracite coal[7] from its limited geographic location in Pennsylvania to markets via railroads and canals; the accessibility of bituminous coal deposits throughout the nation; innovation of technologies that burned coal instead of wood (e.g. steam engines, stoves, lamps, and air furnaces); and consumer propaganda from the coal industry (Melosi, 1985).

Between 1850 and 1900, the portion of America’s energy supplied by coal increased from 9% to 71% (Cook, 1976), and this new energy source began to relax constraints on the size and location of industrial development. People living in and near Pennsylvania (where anthracite coal was initially discovered and regional deforestation had resulted in increasingly expensive firewood) used coal for cooking and heating as early as the 1820s (Sachs, 2015). With the subsequent

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[7] Anthracite coal is a variety that is geologically older, more pure, and has a higher carbon content than the more widespread bituminous variety. Anthracite was found largely in eastern Pennsylvania and given its purity, produced little smoke when burned. Bituminous coal is a geologically younger, less pure variety found in Western Pennsylvania and in deposits across much of the nation. While more easily accessible and cheaper to extract, bituminous coal is “dirtier” and produces significant amount of smoke when burned.

discovery of vast deposits of bituminous coal in western Pennsylvania and states across the nation, coal replaced wood charcoal as the nation's primary industrial fuel, particularly for smelting iron and steel—essential ingredients of the industrial revolution. Other facilities such as glassworks, textile factories, breweries, machine shops, and salt works also adopted coal as a fuel source (Tarr & Clay, 2014). Innovation of the coal-powered stationary steam engine provided the opportunity to disperse industry away from waterpower sites and factories diffused from the hinterlands into cities to access markets and labor (Miller, 1987). No longer limited by the amount of power that could be generated from an adjacent river, facilities also expanded in size and increased production levels, contributing to the rise of large-scale manufacturing and growth of cities to support these operations (Miller, 1987; Sachs, 2015).

The geographical distribution of coal played an important role in driving patterns of industry, population, and transport across America (Cook, 1976). While coal-based steam power permitted far more locational mobility than the water wheel, it was most advantageously utilized near a source of coal (or transportation carrying coal), and thus, the dominant trend of industrialization through the later nineteenth century was a growing concentration of industry in locations favored by large coal deposits (Rosenberg, 1998). During this, period the nation's largest urban-industrial centers were almost exclusively in the Northeast and Midwest with access to Appalachian coal (Pratt, 1981). Proximity to coal fields in Pennsylvania, Alabama, and Illinois, for example, was a major factor in the establishment of steel mills in these locations, which in turn attracted steel-using factories (Cook, 1976). Broadening of job opportunities associated with this urban industrial growth (along with new farming technology that decreased labor needs on farms as well as European immigration) prompted a massive influx of people into these cities which helped drive urban expansion (Cottrell, 1955; Miller, 1987; Olmsted, 1870). As both a fuel and a commodity, coal also influenced the shape of the burgeoning national railroad network (Cook, 1976; Tarr & Clay, 2014). Coal replaced less efficient wood as fuel for locomotives and steamships and increased the power and speed possible with these forms of transport. Tarr and Clay (2014) estimate that by1880, bituminous coal made up over 90% of railroad fuel and remained at that level through the 1920s. It was also the largest single railroad commodity (by tonnage) during this era (Tarr & Clay, 2014). Rail lines were constructed to link sources and markets for coal, and the eventual completion of the national railroad network transformed the American landscape (Melosi & Pratt, 2007).

Urban historian Harold Platt's (1987) case study of Chicago provides an example of how access to coal resources contributed to the emergence of industry, increased population, and rapid urban growth in a region. Chicago was first established as a regional lumber center, but in 1856, geologists discovered huge deposits of high-quality, bituminous coal less than 100 miles south of the city, leading to an influx of 23 million tons of coal per year by 1915 (Benda, 1982; Platt, 1987). The influx of this fuel encouraged energy-intensive industries to establish there, particularly iron, steel, and manufacturing. Platt (1987, p. 12) attributes Chicago's phenomenal growth from 300,000 to 1.5 million people between 1870 and 1900 to this industrial expansion and asserts "the rise of Chicago as the industrial center of the Midwest would not have been possible without abundant energy resources." These energy-based industries also increased the city's demand for physical area leading Benda (1982) to suggest that land use in Chicago was completely driven by the requirements of coal. Along with public transportation (e.g. commuter railroads and omnibus), the demand of industrial facilities for larger areas of land contributed to the spread of cities and a shift away from the mixed land use characteristic of earlier settlements towards the segregation of work and domicile characteristic of many industrial cities (Burchell & Listokin, 1982).

While Chicago was a major coal producer, it was Pittsburgh that served as the nation's energy center in the late-nineteenth and early-twentieth centuries. Tarr and Clay (2014) provide an account of Pittsburg as an "energy capital," a city with a coal seam large enough to make Pennsylvania the United States' leading coal producer and where patterns of industrial development, settlement, and population were shaped by energy resources. Coal mining in Pittsburgh can be traced back to the late 1700s with coal companies building their own "patch towns" adjacent to mining sites around the city to house workers and maintain a steady supply of labor (Tarr & Clay, 2014). As demand for coal grew, regional urban and transportation networks arose to service the coal industry. According to Tarr and Clay (2014), nearby towns like Greensburg, Connellsville, and Uniontown provided associated administrative and financial services, retail and wholesaling services, and mining equipment manufacturing, while regional rail routes were constructed solely to transport coal and coal products. Energy intensive iron and steel production and associated manufacturing were drawn to the city, and the job opportunities attracted population. Factories from these industries employed thousands of workers and formed new "satellite cities" with their own housing, streets, police forces, newspapers, and schools (Miller, 1987; Nye, 1994). Eventually the metropolis subsumed these cities as residential developments filled in intervening space (Miller, 1987). In essence, coal played a major role in influencing the form of urban development in parts of the Northeast and Midwest.

B.2. Oil and Natural Gas

Although coal dominated as an urban-industrial fuel during the mid-nineteenth century, by the early-twentieth century oil and natural gas overtook coal as the nation's primary energy sources (Melosi, 1985; J. C. Williams, 1997). By 1890, the western frontier had been completely settled, and the U.S. had become the world's leading industrial nation (Jackson, 1985; Miller, 1987). America's first commercially producing oil well was drilled in Titusville, Pennsylvania in 1859, but scientists initially struggled to perfect uses for petroleum as they sought to make oil competitive with wood and coal (Black, 2000). In its first decades, petroleum was primarily used for kerosene lighting. Gasoline, a byproduct of kerosene production, was discarded as waste (Cook, 1976). But with the discovery of vast deposits of crude oil in Texas and California, young oil companies aggressively pushed the use of oil as fuel (Pratt, 1981). Consumption of oil as a fuel source began in certain regions and, given the country's growing appetite for energy, did not directly displace the use of coal. The transition to oil was most rapid and thorough in the burgeoning population centers of the West and Southwest where access to coal was limited, readily-available fuel wood had been depleted, and discovery of vast petroleum resources provided an inexpensive energy source to support manufacturing and transportation (Pratt, 1981). While certain uses of coal continue to this day, Yergin (1991) argues that by the mid-twentieth century, oil and natural gas had replaced coal as the nation's "lifeblood." As with prior energy source transitions, the shift to oil and natural gas buoyed urban growth in distinct parts of the country; it also relaxed constraints on development, contributing to increasingly sprawling patterns of urban form.

Between 1900-1920, U.S. energy consumption more than doubled and markets for both coal and oil expanded (Pratt, 1981). This time period coincided with the tail end of the American Industrial Revolution and the beginning of the United States' engagement in World War I between 1914 and 1918. Despite demand for both coal and oil, certain perceived advantages of petroleum fuels over coal fostered a growing transition between these primary energy sources, especially in certain industries and applications. After the discovery of large quantities of available oil in the West, western railroads quickly substituted fuel oil for coal. Pratt (1981) suggests this shift was driven by the low regional cost of the fuel compared to coal, easy access to many new oil fields via the railroad network, low cost of engine conversion, and investments in the young oil industry by railroad owners. By the 1950s, with the adoption of the diesel-electric locomotive engine, coal consumption by railroads across the nation was negligible (Tarr & Clay, 2014). Steamships also began to convert from burning coal to oil around 1900. Those ships carrying petroleum products began to switch to oil, followed by ships sailing from the oil-rich West and Gulf Coasts carrying a variety of commodities (Pratt, 1981). According to Pratt (1981), the U.S. Navy gradually began converting its fleet prior to World War I, starting with the smallest ships around 1910, and by the end of the conflict (circa 1920), nearly the entire U.S. Navy fleet was running on petroleum. Low price, superior performance, the Navy's shift to oil, and savings in shipping space with lower-volume petroleum fuel, all provided strong incentive for remaining ships to transition to oil (Pratt, 1981). In urban areas, air pollution caused by burning coal, led to smoke abatement campaigns and tougher smoke laws in many cities by 1912 (Melosi, 1985, 1987). This buoyed the trend toward substitution fuel oil and natural gas for lighting, heating, cooking, and industrial uses (Cook, 1976). A new market—and a new era in energy—opened as petroleum made possible advances in personal transportation, namely the gasoline-powered internal combustion engine (Yergin, 1991). Cook (1976) sites the explosion of internal combustion engine automobiles and the beginning of national electrification at the onset of the twentieth century as primary causes of soaring demand for gasoline and fuel oil respectively.

Natural gas was largely a companion fuel to oil, unavoidably produced with crude and initially flared in the fields as an unwanted by-product. By the mid-1920s, however, the rising value of gasoline and the vast availability of natural gas led oil refiners to begin powering their own heat intensive refining processes with natural gas as opposed to fuel oil (Pratt, 1981). As many other industrial users followed suit, natural gas production and consumption increased almost as fast as regional and national pipeline systems for its distribution could be constructed. Thus, Pratt (1981) argues, natural gas became a key component in sustaining the transition away from coal by substituting for petroleum in certain markets, so petroleum could be used to meet the rapidly rising demand for gasoline.

Expansion in the use of fuel oil, gasoline, and natural gas accelerated the ascent of oil over coal and by the mid-twentieth century, as Yergin (1991, p. 14) contends, "oil, supplemented by natural gas, toppled King Coal from his throne as the power source for the industrial world." As early as 1950, petroleum and natural gas provided more than half the gross energy input into the nation's economy (Cook, 1976). Estimated consumption of oil had expanded from 6.4 million barrels in 1899 to greater than 300 million barrels in 1920 (Cook, 1976).

This transition in primary energy sources prompted industrial and urban growth in regions of the country where petroleum resources were concentrated. Just as the geographical distribution of coal had influenced a distinctive pattern of urban growth in the coal-rich Northeast and Midwest, Melosi & Pratt (2007) describe how the distribution of oil spawned a different pattern of "Sun Belt" city growth in the nation's West and Southwest. Houston and the Gulf Coast, as well as cities including Los Angeles, Atlanta, Dallas-Fort Worth, Oklahoma City, and Phoenix, produced the bulk of the world's oil from the turn of the twentieth century through the 1960s, and by the 1930's, served as the center of the America's natural gas production as well (Melosi & Pratt, 2007). Oil and natural gas accelerated the growth of these regions by providing abundant, inexpensive industrial and transport fuel. Moreover, oil and natural gas extraction, processing, transport, and consumption facilitated new petro-industrial complexes of oil-related activities including production, refining, shipping, petrochemical processing, research, management, and industry-specific tool manufacturing and construction. These petro-industrial complexes created tens of thousands of jobs, attracted generations of workers, facilitated urban growth, and drove regional prosperity in America's Sun Belt in the early twentieth century (Melosi & Pratt, 2007). Once constrained by lack of direct access to coal deposits, the West and Southwest grew more rapidly than any other parts of the country between 1900 and 1920, fueled in large part by oil and natural gas (Pratt, 1981). The burgeoning urban-industrial sunbelt cities of Los Angeles, San Francisco, Houston, and Dallas nearly tripled in population size from a combined population of 500,000 in 1900 to 1.4 million in 1920, in turn providing an expanding market for the oil and natural gas that fueled their development (Pratt, 1981).

The City of Houston, in particular, is often described as a product of its oil and petrochemical heritage (e.g. Melosi & Pratt, 2007; Platt, 1987; Pratt et al., 2014). Prior to the discovery of oil, Houston was largely cut off from cheap coal and its associated technologies in the nation's North, but the 1901 Spindletop oil gusher shifted the city from a state of relative energy scarcity to one of abundance (Platt, 1987). Melosi and Pratt (2007) suggest it was these oil and natural gas resources that fostered Houston's subsequent emergence as a major metropolis. This assertion is supported by the work of Platt (1987), who provides a detailed case study of the city's urbanization before and after the discovery of oil to illustrate that the presence of regional energy resources facilitated its urban growth.

According to Platt (1987), the reaction of the city after the discovery of oil indicates that significant opportunities for urban expansion hinged upon local availability of cheap fuel. The oil boom boosted existing industries, spawned new ones, and led to expansive growth of the city and its population. For instance, between 1870 and 1900 (prior to the discovery of oil), the region's population grew by approximately 35,000 people, but between 1900 and 1930, it increased by almost 250,000 people, a seven-fold increase in growth over the previous three decades. Platt (1987) points out that this comparison is particularly compelling because other variables that could influence urban growth—geographical position, natural wealth of the surrounding hinterland, patterns of immigration, and the social, political and cultural relationships of city dwellers—remain the same when analyzing a single location. He concludes that the sharp contrast between Houston's growth before and after the discovery of oil illustrates that the region's access to energy resources was a causal factor of its urban growth. Moreover, Platt (1987) contends that the parallel between the discovery of oil in the Southwest and the rise of the Sun Belt cities strongly suggests a causal relationship as well.

The influence of oil on urban development was by no means limited to the Sun Belt. Cities outside of this region that harnessed oil or natural gas resources experienced growth as well. For example, Nye (1990) attributes the town of Munice, Indiana's sudden growth to the discovery and production of nearby natural gas resources beginning in 1885. Between 1889 and 1892, the town's population nearly doubled, as it drew industries whose energy demand could be met with natural gas and migrants from nearby states as well as overseas to work in these industries. Oil and natural gas discoveries in Denver and Wichita around 1900 have also been cited as facilitating the urban growth of these locations by attracting new energy-intensive industries and population (Rose & Clark, 1979). According to Rose and Clark (1979), access to energy resources was a fundamental municipal attraction for industry and whatever a city could deliver—gas, oil, or coal—became vital to urban competition.

Increasingly sprawling urban form also coincided with the rise of oil. The transportability of energy-dense fossil fuels permitted further separation of urban areas from their energy resources and continued to weaken the limits that energy availability once placed on industrial development and urban growth. Cities grew in physical area to support increasing industrial development and larger populations. As industrial developments grew, they demanded more land, which increasingly negated the mixing of residential and industrial land uses (Burchell & Listokin, 1982), so suburban residential zones developed on the outskirts of industrial areas. In certain cases, industrial-residential urban clusters formed around regional oil fields and then merged together to form sprawling metropolitan conurbations. Thus, Yergin (1991) identifies petroleum as the basis of a post-World War II suburbanization movement that transformed the contemporary urban landscape of the entire nation—making possible both where people lived and how they commuted. Similarly, Rose & Clark (1979) argue that fossil fuel energies along with the automobile transportation they supported were critical in facilitating urban decentralization throughout the United States.

In one of the most spectacular examples, oil discoveries in and around the Los Angeles (LA) Basin supported the city's stunning growth and influenced its sprawling configuration (Viehe, 1981; J. C. Williams, 1997). Southern California historian Fred Viehe (1981, 1991) attributes both the location and "spread city" form of urban settlement in California's LA Basin largely to oil discoveries in the region in 1890. Spatially disaggregated oil discoveries attracted industry and population and facilitated the establishment of multiple industrial-residential clusters around various oil fields, as well as around distant refinery sites linked to the oil fields by pipelines (Viehe, 1981, 1991). Less than 65,000 people lived in southern California in 1880, but by 1900, the population had grown by 372% (J. C. Williams, 1997). By 1920, the LA region had become the home of numerous major industries all of which cited "easy accessibility to oil and natural gas as one of the major reasons they moved to southern California" (Viehe, 1981, p. 14). These industries located their administrative headquarters in the city of LA but their factories and warehouses in the industrial suburbs associated with the oil industry thereby creating more jobs and further driving growth in the greater LA region (Viehe, 1981, 1991). The industrial suburbs eventually led to a series of new towns and, as J. C. Williams (1997) explains, by 1930, a suburban network founded by the oil industry occupied much of the LA Basin. Thus, by 1930, energy resources had played a large role in shaping the urban growth of the LA Basin as a network of industrial-residential suburban clusters surrounding the administrative-residential city of LA (J. C. Williams, 1997).

The contention that energy resources played a significant role in shaping the suburbanization of LA is particularly interesting given that LA is typically touted as an example of the transportation theory of suburban sprawl that was first postulated by Sam Bass Warner (1962) in his book *Streetcar Suburbs*. Generally, Warner (1962) postulated that the suburbanization of Boston was induced by the extension of streetcar lines into rural areas that encouraged middle-class movement to such suburbs. This theory has since been amended with other methods of transportation, namely the personal automobile, replacing the streetcar as the means of inter-urban transport and has become a widespread interpretation of the suburbanization process in many locations (Viehe, 1981). While both Viehe (1981) and J. C. Williams (1997) acknowledge that transportation certainly played a role in the urbanization of the LA region, Viehe (1981) points out that inter-urban transportation lines did not reach the LA suburbs, such as Whittier and Fullerton, until well after oil had led to their incorporation. Importantly, both authors conclude that oil resources played a more dominant role in shaping LA's urban form than is widely recognized.

B.3. Environmental Implications of the Mineral Energy Economy

By the close of the nineteenth century, a cultural commitment to harvest resources, industrialize, and expand in the name of progress had become widespread, and this "progress" was equated with the consumption of fossil energy sources (Black, 2000; Melosi, 1987; Sachs, 2015). The direct environmental impacts of energy extraction, processing, distribution, and consumption became more pronounced and destructive in the age of fossil resources, as did the urban growth they fueled (Pasqualetti, 2013; Pratt et al., 2014).

Melosi (1987), Pasqualetti (2013), Sachs (2015), Tarr and Clay (2014), and numerous other authors have detailed the environmental degradation associated with the extraction and processing of coal. Coal mining, whether surface or deep, significantly alters the landscape, geology, surface and groundwater, and vegetation in its vicinity often resulting in contaminated water supplies, toxic waste, land subsidence, erosion, and habitat loss, among other impacts (Tarr & Clay, 2014). Seam scars, pits, shafts, heaps of mining waste, and mining patch towns accumulated around coal mines creating what Pasqualetti (2013) describes as coal energy landscapes. Tarr and Clay (2014) identify sulfuric acid mine drainage as a particularly problematic effect of coal mining that contaminated groundwater aquifers and subsequently affected surface waters in rivers miles from the original source, eradicating aquatic life and vegetation, commercial and recreational fishing, and in some cases, posing public health concerns. Processing of coal resulted in large amounts of smoke and sulfur fumes from coke ovens and the creation of processing wastes which were largely dumped into watercourses causing flooding and contamination (Tarr & Clay, 2014). Yet, as Pasqualetti (2013, p. 17) notes "With little understanding of how to soften coal's impacts, damaged landscapes were endured as an economic necessity, a curse of progress."

Tremendous amounts of smoke from burning coal for fuel also polluted the air in the cities and towns where it was consumed. While industrial development up until the mid-nineteenth century had been a relatively slow process, the pace of industrialization increased vastly in conjunction with the rise of fossil fuel energy sources. Job opportunities from urban industrial growth attracted larger populations, and the concentrated usage of fossil fuel energy in manufacturing, transportation, and domestic heating grew dramatically bringing a new scale of industrial air pollution to cities (Melosi & Pratt, 2007). Coal burning by factories led to localized pollution problems, especially in cities such as Pittsburgh, St. Louis, and Chicago where local topographic and climatic conditions often produced temperature inversions that limited smoke dissipation (Melosi, 1985; Tarr & Lamperes, 1981). Smoke in Pittsburgh caused such terrible air pollution and associated public health effects that it spurred calls to regulate emissions, and the city passed a statute banning the use of bituminous coal or wood by railroads within city limits in 1868 (Sachs, 2015; Tarr & Lamperes, 1981). Culturally, however, smoke was also seen as a visible sign of progress, "a nuisance to be endured," and so this statue was rarely enforced (Tarr & Lamperes, 1981). Yet, by 1912, many cities had implemented successful smoke abatement campaigns to mitigate coal pollution from factories (Melosi, 1985, 1987). Such regulations on the use of coal served as an impetus for local transitions to natural gas and oil fuels in Pittsburgh and other locations. Pratt (1981) suggests that even consumers who switched to oil because of its initially low relative cost compared to coal were later willing to pay a premium rather than switch back to coal because of the lack of offensive smoke.

As with coal, oil and natural gas infrastructure was historically developed and operated with little environmental concern. Since oil and natural gas could not be mined, infrastructure evolved to extract and distribute these resources, including drilling rigs, wells, derricks, storage tanks, refineries, roads, and pipes. The rule of capture—the legal doctrine governing oil production in the U.S. until the 1930s—gave any leaseholder above an oil reservoir the right to pump oil from the field, incentivizing gross overproduction by developers racing to extract from the same fields (Melosi & Pratt, 2007). During this period, chaotic extraction processes resulted in runoff of oil into surrounding rivers, bays and harbors; dangerous fires; evaporation of oil fumes from open oil storage pits; and frequent blowouts, oil spills, and leaking equipment (Melosi & Pratt, 2007). Pasqualetti (2013) notes that while many resources were haphazardly developed during this period in history, petroleum development was unique in terms of the sheer scale of the damage it produced and the novelty of its appearance. In addition to impacting the land, offshore oil wells were drilled from piers in shallow waters along the coast of Summerland, California as early as 1912 affecting the marine environment (Cook, 1976). According to J. C. Williams (1997), petroleum resources soon created a visible, as well as invisible, environment of oil and gas rigs, storage tanks, pipelines, fouled air, and polluted water along California's coast.

O'Rourke and Connolly (2003) describe the major impacts that can arise from oil development and consumption. They cite oil exploration and extraction as invasive processes resulting in deforestation and associated erosion; ecosystem destruction; chemical contamination of land and water; long-term harm to species populations; and health and safety risks to neighboring communities and oil industry workers. Subsequent refining of petroleum products produces volumes of air, water, solid, and hazardous wastes that are often disposed of in onsite pits (O'Rourke & Connolly, 2003). While less so than coal, the consumption of oil and natural gas also produced significant amounts of air pollution. Yet oil and natural gas, like coal before them, became equated with economic progress and the despoiled landscapes they produced were accepted as a necessary ancillary impact, largely stifling early attempts to implement environmental protection measures (Black, 2000; Melosi, 1985).

In addition to the direct impacts of their production and consumption, fossil fuels helped transform the modern city producing a fundamental change in land-use patterns as cities grew and absorbed once rural land surrounding their urban centers (Pratt et al., 2014). Energy use in industrial, domestic, and transportation applications also grew dramatically leading to the "annihilation of space and time" as limits to growth (Pratt et al., 2014). Cities became further separated from their energy sources as they began to rely on steady contributions from complicated extraction, processing and transport of fossil fuels beyond their borders (Pasqualetti & Brown, 2014). This distance between the production and consumption of fossil fuels facilitated a certain level of consumer ignorance in the environmental effects of supplying energy to feed the nation's energy binge.

Simultaneously, however, by the beginning of the twentieth century, there was growing recognition that the unchecked exploitation of resources (including energy resources, but also resources more broadly) to facilitate "progress" was leading to unintended, undesirable urban and environmental consequences. As society reacted to its own growth and industrialization, various urban planning movements[8] took shape to respond to the poor environmental quality, social conditions, and disorder of urban areas. These movements were the origin of comprehensive government-led city planning, zoning, and environmental considerations in planning and increased public provision/regulation of utilities and resources. In addition to local regulations aimed directly at addressing environmental pollution (e.g. smoke control), new federal policies promoting the wise-use of natural resources and wilderness preservation began to replace the resource exploitation and unchecked private extraction common for much of the nineteenth century (Daniels, 2009).[9] Under President Theodore Roosevelt, federal agencies such as the Reclamation Service, U.S. Geological Survey, Bureau of Mines, and the U.S. Forest Service were established and exemplified a shift towards science-based, public resource management and regulation of private resource development (Melosi, 1985; Silveira, 2000).[10]

C. Electricity and the Metropolitan Era (1880 – 1960s)

In addition to the transition from coal to oil, the late-nineteenth and early-twentieth centuries saw a second major development in American energy—the rise of electrical power. Electricity is not

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[8] These efforts included the city beautiful, city efficient, and garden city movements as well as the progressive reform era, all of which sought to eliminate waste, inefficiency, corruption, and injustice by transitioning from piecemeal development to city- and regional-scale planning of urban areas. Daniels (2009), Miller (1987), and Peterson (2009) provide overviews of these efforts.

[9] These policies reflected an emerging ideological divide between the conservationist view of "wise use" of resources with a balance between immediate and long-term production as necessary for sustained economic yield (Daniels, 2009; Silveira, 2000) verses the preservationist view of nature as having value independent of being a resource for human consumption which, as documented by Nash (2001), arose from diverse beliefs including nationalism (nature as national treasure); commercialism (nature for tourism and recreation); spiritualism (wilderness as regenerative); ecology (nature as biologically rich); and aestheticism (nature as beauty).

[10] Mineral and water rights for much of the nineteenth century followed the legal doctrine of prior appropriation under which these resources could be claimed by private individuals through posting of a notice and recording with the local county government giving the owner a perpetual right to the resource that could be sold by the claimer for profit. By 1891, concerned with private exploitation of natural resources, Congress established the Land Law Revision Act giving the Secretary of Interior the power to regulate the occupancy and use of federal forest reserves; issue temporary, revocable rights of way for hydroelectric development. By 1920, the Water Power Act was passed and essentially codified permits for hydroelectric development that included 50-year leases and conservation fees. This amounted to government regulation of private use of natural resources.

a primary source of energy but a secondary form that can be generated from primary sources and efficiently transmitted. Thus, electrification did not replace primary sources of energy; it further commodified them—augmenting the availability of energy and distancing energy production from consumption. Electrification brought further liberation from locational constraints on industrial and urban development by reducing the competitive advantage of locating near primary energy sources, thereby enabling urban growth in new regions of the country (Burchell & Listokin, 1982; Liddle & Lung, 2013; Rosenberg, 1998). It also played a role in the deconcentration of urban areas through early uses in transportation and later the spread of extensive electric distribution infrastructure (Platt, 1991). Yet similar to the sources of power that preceded it, as electricity became increasingly important to modern society, the influence of its production, transmission, and consumption on the physical environment also became profound in its own right (Melosi, 1985, 1990; Tarr, 1984).

Although electricity had been experimented with in Europe as early as 1730 and the means to employ electrical power on a large-scale had been developed in the early nineteenth century, it was Thomas Edison's perfection of the incandescent light bulb in 1879 and development of an entire electrical generation and distribution system by 1882 that eventually stimulated the early electrification of the United States (Melosi, 1985; Rudolph & Ridley, 1986). Limited by existing technology, early electrical systems were decentralized, consisting of small generators in urban areas that supplied nearby lighting systems through direct current (DC) distribution networks. At this stage, the profitability of supplying electrical power was relatively low given the limited demand of nighttime lighting applications, so early electric companies sought to geographically expand and diversify electrical demand to make their ventures more profitable (Rudolph & Ridley, 1986). With the invention of alternating current (AC) transmission in the 1890s came the opportunity to carry high-voltage electricity across vast distances and capture more market share. At the same time, the market for electrical power was growing to include urban transportation and manufacturing uses with the invention of the electric streetcar and steam turbine electric generator. Suppliers of electricity competed for a larger share of expanding urban markets with each other, as well as wood and coal distributors, employing elaborate promotional campaigns and boosting generation and distribution facilities (Rose & Clark, 1979). Household electrical consumption initially remained minimal due to the limits of distribution networks and the cost of replacing existing appliances with electric ones (Nye, 1990). But between 1917 and 1930, the number of residences served increased from 6 million to 20 million, and by 1929, the United States was producing more electrical power than the rest of the world combined (Melosi, 1987). By this time, utilities were centralizing power production by constructing massive generating units and AC transmission networks that efficiently served entire regions.

Electricity was first directed towards industrial and transportation applications and Rudolph and Ridley (1986) suggest that "what fire had been for early man was a rough draft for the force electricity took on" citing its role in running hundreds of thousands of industrial motors. The adoption of electricity to industrial and manufacturing applications influenced the design of factories and diminished constraints on their location. While economies of scale associated with large generating plants led electric power generation itself to become more centralized, the ability to transmit electricity long distances further reduced the once powerful advantage of proximity to primary energy resources facilitating decentralization in the location of industrial activity (Nye, 1990, 1994; Rosenberg, 1998). Factories could now diffuse into and around cities, wherever electrical lines provided access to power for their machinery. In a "dramatic example of how alternating current [electricity transmission] affected factory location" Nye (1990 p. 196) describes how the construction of Folsom Dam in California in 1893 was originally planned to encourage development of an industrial city at the site, but, being completed after the introduction of AC transmission, its electricity was instead carried 20 miles to Sacramento where factories could be more conveniently located in proximity to urban areas. Factories themselves also began to take on new form. Steam-powered factories had largely been multi-story buildings with central ground-floor steam engines powering overhead belting systems in stacked workspaces; however, new factories that relied on electricity were often built as single story, horizontally expansive buildings that efficiently accommodated assembly lines and increased levels of production (J. C. Williams, 1997). Henry Ford's Highland Park auto plant in Detroit, for instance, was a long, single story building that relied entirely on electrical drive motors to run equipment and is often cited as having pioneered the assembly line (Nye, 1994).

Decades before the automobile became America's primary means of transportation, the implementation of electrical power led to changes in urban transportation and a shift toward increasingly dispersed urban form via electrification of the streetcar (or trolley) and the development of extensive networks of electric streetcar lines. Authors such as Jackson (1985) and Miller (1987) argue that the electric streetcar facilitated radial growth and contributed to the physical layout of outlying suburbs. According to Nye (1990), adopting electricity made possible the "streetcar suburb" with electric-powered trolleys enlarging the urban landscape and reaching far out into the countryside to integrate smaller communities into the urban market. For example, in Munice, Indiana, Nye (1990) notes the electric trolley system defined the growth of five suburbs, while Platt (1987) similarly suggests electric streetcars contributed to the build-up of Chicago's outlying suburbs and made practical their annexation. By 1895, trolleys were operating on 10,000 miles of track in 850 cities and up until the introduction of the automobile in the 1920s, suburban real estate was largely concentrated around these lines (Jackson, 1985; Miller, 1987). Electrification even influenced the locations of developments such as amusement parks which were often built at the end of streetcar lines in order to help balance the electrical load because they consumed electricity at night and on weekends when few people road the electric streetcars (Nye, 1990). Thus, Nye (1990) suggests in cities such as Munice, electrical infrastructure had begun to shape the amusements, the appearance of downtown, and the contours of the suburbs.

Electrical networks expanded through the first half of the twentieth century, and along with the automobile, were instrumental in facilitating the transformation of cities into large, decentralized metropolises (Melosi, 1987; Owens, 1986; Pasqualetti & Brown, 2014; Platt, 1991; Tarr, 1984). Throughout the 1920s and 1930s, electrical systems continued to expand and early electrical industry competition gave way to a regulated natural monopoly structure as a few large electrical corporations acquired smaller firms, vertically-integrated generation, transmission, and distribution functions, and captured economies of scale, creating barriers to further entry (Hirsh, 2002).[11] These newly formed electrical utilities constructed massive generating units and transmission and distribution networks that supplied entire regions. For example, a single electrical system served 6,000 square miles and 195 communities in the Chicago area by 1924 (Melosi, 1985).[12] The spread of power distribution grids to outlying areas supplied amenities that previously had only been available in the central city and electric trolleys, followed by the automobile increased personal mobility (Platt, 1991). These factors permitted urban growth to spread radially and at decreasing densities as people spread out to acquire more personal space (Owens, 1986; Pasqualetti & Brown, 2014). In his 1915 work *Cities in Evolution*, urban theorist Patrick Geddes argued that by amplifying the locational flexibility of industry and people, electric power and motorized transport influenced cities, such as Chicago, to spread and merge into continuous urban-industrial complexes he termed "conurbations" (Hall, 2002). Similarly, Burchell and Listokin (1982, p. 9) suggest that the advent of inexpensive new energy resources such as electrical energy, along with the introduction of the automobile, served to remove most of the vestigial restraints of energy on urban development, stating "population and industry could now be diffused, first to the outer limits of the city, then to the near and far suburbs, and finally, to the exurbs and rural fringes." They also note that these expanded and scattered metropolitan forms grew to the point where they joined their neighbors as a megalopolis and that portions of the metropolitan area that did not provide this new spatial freedom (i.e. urban centers) saw population declines.

Electrical infrastructure became imperative to urban competition and regions around the country sought to provide access to cheap electrical power to drive regional economic development through industrialization and urban growth. In a dramatic reversal from the time when cities were founded specifically because energy resources were nearby, Pasqualetti and Brown (2014) identify Phoenix and Atlanta as urban areas located more than 200 miles from significant supplies of oil, natural gas, coal, uranium, or hydropower that support large populations and economies by importing electrical power. As early as the 1930s, Phoenix businessmen were proclaiming "electric energy is as necessary as water and air for the existence of modern economic life" and envisioning a future in which vast amounts of cheap electricity created rapid industrialization of the region (Needham, 2011, p. 248). Coal-fired power plants were eventually constructed on Navajo lands in the distant Four Corners area of the Southwest and provided reliable, inexpensive electricity not only to Phoenix but the entire Southwest. The provisioning of such cheap electricity helped spur settlement and growth of the Sun Belt Southwest region by providing power not only for industrialization, but also for climate control technologies such as

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[11] By the end of the 1920s, 10 electric utilities controlled approximately 72% of the nation's electric power (Melosi, 1987). These utility holding companies also owned real estate businesses, railroads, streetcar lines, water companies and other businesses giving them strong political influence at the local level and allowing them to play a large role in shaping industrialization, the environment, and the concentration of economic power (Rudolph & Ridley, 1986). Soon the conservation movement in the United States was focused on government regulation of private development, and New Deal era policies, including the Public Utility Holding Company Act and Federal Power Act of 1935, broke up the conglomerates by limiting the size of utility holdings and mandating government regulation of electric production in the public interest to ensure reasonable electricity rates. The private companies largely accepted public regulation, however, as part of a "utility consensus" which legally protected their natural monopolies, institutionalized their economic and political influence, and slowed the development of public power systems (Hirsh, 2002; Rudolph & Ridley, 1986).

[12] In contrast to private electric companies, some municipalities, such as Cleveland, developed their own public power companies that supplied electricity to residents. Municipal power systems were the minority, however.

air conditioning (Dale et al., 2011). Needham (2011, p. 262) thus concludes that the power lines stretching from Four Corners "created the sunbelt Southwest…its peripheral metropolitan areas tied indelibly to the energy-rich Navajo landscape at its center." When nuclear power came online in the 1960s, the location of nuclear plants similarly encouraged increased urban development in nearby cities such as Oak Ridge, Tennessee. Even regions that already had access to abundant primary sources of energy were able to attract additional industrial development with electrical infrastructure. For instance, after the construction of the hydroelectric power station at Niagara Falls, numerous aluminum and chemical companies built factory districts nearby using to tap into the inexpensive power (Nye, 1994).

Rural electrification followed urban electrification and was often touted as a way to improve social and economic conditions (J. C. Williams, 1997). In some cases, however, the use of electrification as a means of regional economic development produced unintended consequences. The Tennessee Valley Authority (TVA), for example, sought to revitalize one of the regions hardest hit by the Great Depression and encourage continued farming through public production of hydroelectric power, rural electrification, reforestation, soil conservation, recreation, and rural community building (Daniels, 2009; Gray, 2005; F. Steiner, Young, & Zube, 1988). The construction of multiple hydroelectric dams achieved the intent of providing low cost electricity to the rural region; however, instead of encouraging continued agrarian lifestyle, electrification had the effect of depopulating farms by revolutionizing productivity and necessitating fewer farmers to farm the land (Nye, 1990). Moreover, rural electrification brought the city to the country by luring residential development past the suburban fringe in a continued process of urban deconcentration and leading to "energy boom" industrial communities that sprang up as a result of the hydroelectric construction (Burchell & Listokin, 1982; Nye, 1990). The number of people who found employment opportunities in non-farm activities almost doubled in the TVA's power service region between 1929 and 1954, while the net gain in manufacturing plants numbered more than 2000 (Clapp, 1955). The TVA has explicitly recognized this effect, suggesting that the impacts of building a new power plant in a rural region are likely to include conversion of prime farmland to industrial/residential uses associated with urban growth as power plants attract new industrial development to the region (Tennessee Valley Authority, 1995).

After World War II, electricity exemplified the technological essence of modernity—using science to overcome the constraints of the environment and serving as a tool for humans to refashion landscapes (Kinkela, 2009; Nye, 1998; J. C. Williams, 1997). Production, distribution, and consumption of electrical power increased with national economic growth; the "electronic revolution" that brought televisions and early computers into American homes and businesses; and, modernist suburban development[13] in the postwar era. Electric utilities continued to develop large, centralized systems through what Hirsh (2002) describes as a self-perpetuating grow and build strategy—electrification encouraged expanding consumer bases through urban and industrial growth; utilities built larger, more efficient plants to supply the demand and keep rates low; and, low rates in turn encouraged consumers to consume more electricity which necessitated more supply. Electricity was viewed as the child of science—clean, unseen, powerful, efficient—and holding the promise of better living (J. C. Williams, 1997). According

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[13] Modernist movements such as urban renewal sought to remove urban blight, segregate land use through zoning, and plan and develop uniform, low-density, peripheral communities on a grand scale (Kinkela, 2009).

to Rose and Clark (1979), consumers operated in a cultural milieu in which increased inputs of energy promised clean homes, safer neighborhoods, improved schools, wider opportunities for exercising professional skills and tastes, and amore competitive position for firms.[14] New access to electricity fed all kinds of consumerism (vacuum cleaners, dishwashers, and televisions, to name a few) and the mass production of new electrical appliances (Melosi, 1985; Sachs, 2015). This grow and build strategy carried even further the spatial trend of the "high-energy society," increasing the availability of energy at progressively lower unit costs and further separating energy production and consumption (Bridge et al., 2013; Nye, 1990). Over time, isolated islands of power were replaced by the national scale grid as we know it today – an infrastructure system with more than 17,000 central station power plants tied to load centers via a ubiquitous web of hundreds of thousands of miles of transmission and distribution lines (Bridge et al., 2013; Pasqualetti, 2013).

C.1 Environmental Implications of the Electric Energy Economy

Rapid growth of power production was made possible by electrical means to generate and distribute power from central power stations, and as electricity became increasingly integrated into American society, its influence on the physical environment was profound (Melosi, 1985, 1990; Tarr, 1984). Electricity can be generated from various primary energy sources. Through time, production at a national level has always been from a mixed resource base, with one source or another typically serving as the dominant fuel for electricity. The generating facilities constructed to convert these energy sources to electrical power, as well as the transmission lines erected to carry electricity to consumers, had direct effects on the environment.

In the 1920s and 1930s, the development of hydroelectric power was regarded as a fundamental part of the future of the United States and incredibly ambitious projects like the Hoover Dam were undertaken to meet growing demands for electricity (Cook, 1976; Sachs, 2015). Unlike the early use of run of the river water flows to power mills and factories directly, hydroelectric plants involved the construction of dams at sites with high head (waterfall height), large discharge (flow rate), and large storage capacity (reservoirs) (Cook, 1976). Damming of waterways inundated the reservoir areas behind them converting landscapes, habitats, and land uses that once existed to open water. As Pasqualetti (2013) notes, these reservoirs can also be viewed as beneficial in terms of their scenic and recreational attributes. Beyond the conversion of large areas to open water reservoir, hydroelectric facilities can cause other environmental consequences such as increasing loss of water supply due to evaporation; changing the flow, temperature, and sedimentation regimes downstream of dams; and, barring upstream passage of aquatic species.

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[14] While outside the scope of this analysis, it would be remiss not to note that there was a socio-economic spatial dimension to this new culture of electrification as well. The sale of appliances and the consumption of increasing amounts of electricity corresponded closely with household income. For example, Rose and Clark (1979) describe how by the mid-1930s, Kansas City was divided socially and economically at about 31st Street and that division corresponded with the energy-intensive and the low-energy districts. North of 31st resided those who largely lacked sufficient resources to upgrade their homes for electricity or purchase electrical appliances, while to the South, wealthier individuals built new homes and purchased light, heat, and power, as well as household appliances in great numbers (Rose & Clark, 1979). The issue of uneven economic access to what many today consider a basic necessity remains a challenge, even in developed nations such as the United States (e.g. see Harrison & Popke, 2011).

As the nation's prime hydroelectric sites were built out and with demand for electricity continuing to grow, the share of the country's total electric demand that could be supplied by hydropower began diminishing. Electrical utilities increasingly turned to steam turbine electric generators and fossil fuels to produce electricity. By the end of World War I, electric utilities had become major coal consumers (Tarr & Clay, 2014; J. C. Williams, 1997). In locations such as California, where coal was scarce, natural gas (and to a smaller extent, oil) also fueled electrical generation after hydropower sites were built out (Tarr & Clay, 2014; J. C. Williams, 1997). The combustion of fossil fuels to heat boilers, produce steam, and thereby generate electricity, releases air pollutants such as carbon dioxide, sulfur and nitrogen oxides, and particulate matter. These air pollutants lead to acid rain, the formation of ground level ozone and smog, respiratory effects in humans, and climate change. Burning coal also creates ash residue which coal-fired power plants often mix with water and store as ash sludge in retention ponds. Such waste is considered hazardous material and has polluted soil and waterways in cases where retention ponds have failed (U.S. Energy Information Administration, 2017). J. C. Williams (1997) notes that at a national level, coal remained the dominant fuel for electric generation through the 1960s, even as coal-fired electric plants were publically criticized for air pollution and promotion of environmentally-damaging coal mining practices as early as the 1950s.

Post World War II, the United States sought to develop peaceful uses of atomic energy and one focus of this effort was harnessing the potential to develop commercial electricity with nuclear power. Between 1946 and 1954, there was little progress towards commercial nuclear power as civilian projects remained subordinate to weapons development: the capital cost of building and operating a nuclear plant was a barrier to entry for most utilities; coal interests actively opposed development of the new technology; and demand for electricity from nuclear power was negligible given plentiful, cheap fossil fuels (Melosi, 2013). With the passage of the Atomic Energy Act of 1954, the Price-Anderson Act of 1957, and initiatives taken by the post-war Atomic Energy Commission, the federal government sought to promote development of commercial nuclear power plants through financial incentives, a reactor demonstration program, and indemnification measures for those building and operating plants (Melosi, 2013). The first commercial nuclear power plant in the United States went into service in 1957 at Shippingport, Pennsylvania (Cook, 1976), but through the early 1960s, the use of nuclear power to generate electricity remained novel and not well established, with only six U.S. plants operating by 1962 (J. S. Walker, 1992). As electrical demand continued to increase into the 1960s, the electric power industry's grow and build strategy prompted utilities to expand the resource base from which they generated power (Williams 1997). Utilities believed that nuclear plants could offer "economies of scale" over fossil fuel plants and by the late 1960s were ordering massive reactors (1.1 to 1.2 gigawatts (GW) in capacity) with the intent of lowering the unit cost of power produced (Melosi, 2013). The early-1970s through the mid-1980s was an extraordinary period of investment in power plant construction driven largely by huge spending for nuclear power stations (Masters, 2004).

From its beginnings, however, nuclear power generation was met with social and environmental concerns (Williams 1997). Much like fossil fuels, obtaining uranium requires mining operations, mills, and enrichment facilities, which impact landscapes and can pose radiation health hazards to workers and those living nearby. Nuclear generating facilities require large areas of land to house massive power plants, cooling infrastructure, radiation containment structures, exclusion zones, and onsite waste storage (Pasqualetti, 2013). While these facilities do not emit carbon dioxide or other air pollutants, they can produce thermal pollution of nearby water bodies, which are used as both sources and receptacles for cooling process water. Early nuclear plants used cooling water less efficiently than fossil fuel plants, producing massive amounts of return water at temperatures 10-20 degrees Fahrenheit greater than source water, which impacted aquatic life (Melosi, 2013). Onsite cooling ponds and towers later mitigated this impact for new plants along inland waterways, but added to the land requirements and cost of such nuclear facilities (Melosi, 2013).

The biggest debate over nuclear power focused on reactor safety. Nuclear power plants produce low- to high-level radioactive waste (U.S. Energy Information Administration, 2017) and storage, as well as disposal, of such wastes is seen as a principal unresolved problem (Williams 1997).[15] Accidents can occur anywhere along the fuel cycle—from uranium mining and transport, to power production, to waste disposal—with the potential for significant impacts to public health and the environment (Melosi, 2013). In California, seismic issues and the potential for nuclear accidents have been concerns voiced against proposed nuclear development, for example at Bodega Bay (Williams 1997). The rise of the modern environmental movement in the 1960s pushed the environmental critique of nuclear beyond "not in my backyard" issues, to questions of whether nuclear power, with its associated risks, should be part of the nation's energy mix under any circumstance (Melosi, 2013). Yet by 1979, there were 70 nuclear plants operating in the United States, and they supplied approximately 14% of the nation's electricity.

In addition to the environmental consequences associated with generating electricity from various primary energy sources, electrical transmission and distribution infrastructure affect the quality of the environment. At the turn of the twentieth century, most transmission systems ran for relatively short distances as the bulk of electricity was generated near urban areas; however, within a decade or two, transmission lines hundreds of miles long were connecting dams in the mountains to distant cities (Levy, 1997). The primary impacts associated with such infrastructure are the maintenance of rights-of-way free of vegetation around the lines as well as their visual presence. Given this, as Pasqualetti (2013) notes, the perceived landscape impacts of power lines can vary widely according to factors of topography, land use, and vegetation. For example, in natural habitats, repeated disturbances to create and maintain clear swaths of land for power line rights-of-way can affect plant populations and wildlife (Bare et al., 2009; U.S. Energy Information Administration, 2017). In scenic natural areas, the conspicuous visual disruption of power lines and transmission towers traversing across the landscape is also aesthetically offensive to many people. Even in developed urban environments, the siting of electric transmission and distribution infrastructure such as power lines, substations, and transformer banks has elicited public outcry over unavoidable visual presence, diminished land values, and suspected human health effects (Levy, 1997; Pasqualetti & Brown, 2014).

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[15] The U.S. Government identified permanent geologic storage as the safest solution but the question of where to locate such storage is subject to significant environmental, social, and political conflict. After much debate, in 1987 Congress directed the U.S. Department of Energy to study Yucca Mountain, Nevada as the location for the nation's nuclear waste storage. According to Melosi (2013), Yucca Mountain was not the best site from a geologic standpoint but was the most politically viable. In 2008, the department filed for a construction permit to build a repository, but in 2009 President Obama suspended its licensing. Currently, there is no licensed national repository, and approximately 70,000 tons of nuclear waste is being stored onsite at nuclear power plants across the United States (DiChristopher, 2017).

By facilitating increasingly sprawling urban form and relaxing constraints on urban growth in areas further and further from primary energy sources, the adoption of electricity also indirectly affected the environment through the new expansive urban development it enabled. Owens (1979) suggests that the profligate use of fuel for transportation and electricity to power homes and businesses created decreasing densities and increasing physical separation of activities. She concedes that during this era of perceived energy abundance, planning and development of individual buildings, neighborhoods, and even cities proceeded with little or no regard for energy efficiency (Owens, 1979). This culminated in the classic picture of the sprawling suburbs of the latter half of the twentieth century and massive metropolitan areas amass with consumers who were increasingly out of touch with the sources and costs of the energy powering their lifestyles (Sachs, 2015).

Despite the direct and indirect environmental implications of the nation's rapidly increasing production and consumption of electricity, during the first half of the twentieth century, technological optimism overshadowed any environmental concerns associated with growing electrical power networks. Americans associated technological advance (including electricity) with military victory, economic dominance, and better standards of living (J. C. Williams, 1997). The modernist planning paradigm of the time painted nature as a backdrop for human endeavors and refashioned landscapes with utter disregard for ecological connections between humans and nature (Kinkela, 2009). For most Americans, technology was seen as a tool for conquering environmental obstacles and harnessing natural resources—power plants, transmission lines, and even electronic appliances were seen as ubiquitous symbols of American progress (Levy, 1997; Pasqualetti, 2013; J. C. Williams, 1997). This belief in the technological sublime eclipsed issues such as visual impact, thermal water pollution, air pollution, radiation hazard, sprawling urban development, and other environmental impacts associated with electric power production, transmission, and consumption (J. C. Williams, 1997).

However, by mid-20th century, technological optimism and tacit acceptance of the environmental costs of energy production and consumption began to erode. Energy landscapes and their environmental implications became increasingly difficult to dismiss as unavoidable ancillaries of progress (Pasqualetti, 2013).

D. Energy Aftermath: Environmental Awareness and Energy Security (1960s-Present)

According to energy and environmental scholar Vaclav Smil (2008), by the beginning of the 1960s, environmental concerns emerged as a major preoccupation of industrial civilization and there was little doubt that energy industries and energy use were the leading causes of environmental degradation and pollution. The 1950s and 1960s were an era of particularly cheap and abundant energy for the United States, and the nation's highly energy-intensive economic system had continued to develop with demand for electricity growing at rate of approximately 7% annually (Melosi, 2013; Owens, 1986). In addition to domestic energy development, the United States became increasingly dependent on imported oil. Environmental repercussions from surface mining of coal, air pollution from coal and cars, landscape fragmentation by electrical transmission infrastructure, health and environmental risks of nuclear power, major oil spills, and other energy impacts in large part galvanized the environmental consequences of such energy exploitation in the eyes of the public (Melosi 1987). By the 1960s, many began reconsidering the relationship between the environment and infrastructures of energy production and consumption. A number of new federal laws passed with a broad objective of protecting environmental quality. On the heels of this environmental awareness, the Organization of Petroleum Exporting Countries (OPEC) placed an embargo on oil in 1973 that led to radically increased oil prices, which stressed utility systems, and in turn, increased electricity rates (Hirsh, 2002). Energy scarcity led to reduced consumption, concern over energy independence, and calls for limits to unrestrained economic and urban growth. Environmental and scarcity concerns, along with technological stasis in the electricity sector and the passage of the 1978 Public Utility Regulatory Policy Act (PURPA), began eroding the electric utility consensus and stimulated the first real push for alternative means of producing power including from renewable resources such as solar, wind, and geothermal (Hirsh, 2002). Electricity sector deregulation and restructuring in the 1990s, as well as acknowledgement of the links between conventional energy production, greenhouse gas emissions, and climate change have, today, paved the way for another major primary energy transition to renewable resources.

In the 1960s, public focus on energy and the environment was just one component of a broader cultural shift in the United States through which American environmental values were starting to broaden beyond preservation and efficient use of natural resources to a wider emphasis on ecology and environmental quality. Ecology, with its focus on the reciprocal relationship between the environment and living organisms, emerged as a science in the early twentieth century and became a popular concept by the 1960s (Melosi, 2013). Rachel Carson's seminal book, *Silent Spring,* was published in 1962 and effectively demonstrated the ecological and human health impacts of the postwar modernist era's conventional pesticides (Carson, 2002). Carson argued that science and technology had been insulated from public input, and her book sparked public activism against the environmental threats from industrial production (Kinkela, 2009; Silveira, 2000). Geritt Hardin (1968) described the tragedy of the commons and, along with ecological economists who emphasized the finite nature of the world's resources (e.g. Boulding, 1966; Meadows, 1972), critiqued unlimited growth as unmaintainable. Amidst increasing perception that urbanization placed a large burden on the natural environment, urban sprawl was labeled as a metropolitan and environmental crisis. The public became aware that environmental quality was linked to technology, industry, and economy and distrust mounted against the existing institutional structures that shaped society (Silveira, 2000). The first "Earth Day" took place in 1970. J. C. Williams (1997) describes how, as part of a growing culture of dissent against the ubiquitous technocratic idea of progress, environmentalists challenged the traditional vision of a technologically-dominated and despoiled environment. Instead, technological historian Samuel P. Hays (1981, as cited in Stine & Tarr, 1998) argues, the postwar environmental movement was distinguished by the view of science and technology as means to improve environmental conditions.

Better planning and regulation were also seen as essential to addressing environmental degradation. New federal environmental and natural resource regulations reflected the shifting cultural emphasis towards protecting environmental quality. Amid a series of environmental catastrophes including the Santa Barbara Oil Spill and Cuyahoga River fire both in 1969, the Love Canal toxic waste dump in New York, and the partial meltdown of a nuclear reactor at

Three Mile Island in Pennsylvania in 1979, the federal government established the Environmental Protection Agency (EPA) in 1970 and passed sweeping environmental legislation focused on restoration and protection of the environment.[16] Modern environmental planning emerged as a discipline rooted in the concept of ecological determinism (McHarg, 2006; F. Steiner, 2004) and suitability analysis techniques (McHarg, 1969) to better understand environmental opportunities and constraints to human uses. At the same time, grassroots community groups and national environmental organizations arose as the approach to environmental protection transformed from primarily top-down resource control by technical "experts" to include bottom-up action by citizens (Silviera, 2000).

While new environmental attitudes and regulations in the 1960s increased the focus on the environmental effects of energy industry actions like resource extraction and power production, Pasqualetti and Brown (2014) note that until the oil embargo of 1973,[17] energy consumption was mostly an abstract topic, something individuals took for granted when flipping on a light switch or pumping gas. Historically, the United States relied relatively little on imports of energy from other countries, but growing energy demand and cheap foreign oil in the 1940s and 1950s led the United States to increase imports of oil from other nations. In the 1960s, countries with vast oil reserves that were supplying the United States, such as those in the Middle East, Africa, and Latin America, sought to acquire greater control over their oil resources and formed OPEC (Melosi, 1987). In October of 1973, Arab nations participating in OPEC imposed an oil embargo on the United States in retaliation for American aid to Israel in the then ongoing Arab-Israeli ("Yom Kippur") War. Although the embargo itself lasted only six months (ending in March 1974), the embargo led to dramatically increased oil prices and concerns over scarcity in the United States (Melosi, 1987). Melosi (2013) argues that at the time the United States was particularly vulnerable to these changes because by 1973 the nation's consumption of oil was double that of the 1950s yet domestic production had diminished, necessitating foreign imports to meet nearly 40% of U.S. demand. The embargo was followed by the 1979 Iranian Revolution, which precipitated a new round of rising oil prices and further cutbacks in oil imports lasting into the 1980s. The nation faced rationing of gasoline and soaring regional electricity prices due to the cost of generation in regions of the country that depended on oil (French, 2017). These consequences led the public to begin considering the finite nature of fossil energy resources, America's dependence on foreign oil, and even their own energy consumption (J. C. Williams, 1997).

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[16] Examples of such legislation include the National Environmental Policy Act (NEPA) in 1969, Clean Air Act Amendments in 1970, Clean Water Act and Coastal Zone Management Act in 1972, National Forest Management Act and Resource Conservation and Recovery Act in 1976, and the Comprehensive Environmental Response, Compensation, and Liability Act of 1980. Many of these laws amounted to command and control regulation by government of private industry actions, including energy source extraction and power production. But after rolling back of regulation under Reagan in the 1980s and a shift towards state regulation under Clinton in the 1990s, emerging regulatory measures encouraged markets to produce more environmentally beneficial outcomes through financial incentives and regulatory flexibility. The shift from command and control regulation to a market based approach is illustrated by the Clean Air Act, which initially mandated industry use "best available technology" to control air pollution, but after amendments in 1990, introduced programs such as sulfur dioxide cap and trade that provided strong financial incentives to reduce pollution while letting industry decide how to achieve the reduction.

[17] A full discussion of the politics, causes, and effects of the 1973 embargo is outside the scope of this analysis. Merrill (2007) and Yergin (1991) are good starting points for resources on this topic.

Amidst this ecological and energy scarcity context, popular recognition of existing energy landscapes began, and new ideologies of suitable energy production and consumption emerged. Works such as *The Machine in the Garden* (Marx, 1967) inspired substantial thought on the relationship between energy technologies and the environment (Pasqualetti, 2013). By 1972, the U.S. government had established the Office of Technology Assessment to evaluate unintended consequences of technology, most of which were environmental in nature, and the concept of "Appropriate Technology" began generating public appeal (Pursell, 1993; Schumacher, 1973; Stine & Tarr, 1998). Pursell (1993) describes the rise of the Appropriate Technology movement in the United States as a critique of both American foreign aid ideologies in developing nations and the "overdevelopment" of technological systems in the United States itself. He asserts that at its core, the movement sought to reorient technology towards affordable, accessible, locally suitable, autonomous, ecologically sound applications. As captured by Schumacher's (1973) *Small is Beautiful*, Amory Lovins' (1976) "Energy Strategy: The Road Not Taken?", and Herman Daly's (1977) *Steady-State Economics*, a key focus of the Appropriate Technology movement centered on energy systems.[18] In contrast to complex, large-scale, centralized, expensive, autocratic, fossil- and nuclear-fueled energy infrastructures, Lovins and others championed conservation, energy efficiency, and simple, small-scale, diverse, democratic, renewable energy technologies such as solar energy, windmills, low-head hydroelectric generation, and alternative fuels like methane gas and ethanol (Pursell, 1993). The federal government launched research and development initiatives for such alternative technologies, including a solar energy research program with $17 million annually in 1974 that peaked at $500 million annually in the early 1980s, and similar initiatives for wind power and other renewable energy sources (J. C. Williams, 1997).

U.S. energy policy in the immediate wake of the environmental movement and energy crisis became more coordinated and reflected a closer linkage between energy and environmental considerations. President Carter established the Department of Energy in 1977 to consolidate federal energy policy, research, and development programs. Notably, in 1978, he signed into law the National Energy Act, which included PURPA as well as regulations to encourage energy efficiency and reduce the use of oil and natural gas for electricity production, although Joskow (2001) notes that this had the effect of pushing electric utilities to increase generation from coal. According to Joskow (2001), PURPA sought to combine energy security goals with environmental protection goals by stimulating electricity production from thermally-efficient cogeneration plants and renewable fuels. Title II of PURPA required electric utilities to buy power from "qualifying facilities"—non-utility cogeneration plants and small power production facilities using renewable and waste fuels—under long-term contracts at the "avoided cost" of having to produce the power themselves (Weare, 2003). States were given leeway to set the avoided cost prices under PURPA, which increased their involvement in energy policy (Joskow, 2001). In 1980, Carter signed the Energy Security Act intended to increase domestic energy supplies and reduce consumption. This act consisted of six pieces of legislation[19] that provided

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[18] To be sure, the Appropriate Technology movement also focused on a broader range of technologies including bicycles and mass transit, recycling and the use of natural building materials, composting and sustainable (often organic) agriculture.

[19] These pieces of legislation included the U.S. Synthetic Fuels Corporation Act, Biomass Energy and Alcohol Fuels Act, Renewable Energy Resources Act, Solar Energy and Energy Conservation Act, Geothermal Energy Act, and Ocean Thermal Energy Conversion Act.

subsidies for alternative energy supplies and energy efficiency.

While the Appropriate Technology ideology and government's focus on developing alternative energy sources enjoyed traction during the height of the environmental movement and energy crisis, these efforts waned somewhat under a variety of factors in the 1980s. Pursell (1993) describes the Appropriate Technology movement as a victim of roll-back of government support under the Reagan administration, the inability to effectively challenge the entrenched large technological systems already in place, and the "re-masculinization" of American culture in the aftermath of the Vietnam War. Nationally, oil and natural gas prices peaked in the early 1980s and fell through the 1990s (Hirsh, 2002). Joskow (2001) argues that as energy prices fell and fossil fuel supply shortages disappeared, interest in energy policy quickly declined, resulting in few significant new federal energy policy initiatives during the Reagan administration or the first years of the George H. W. Bush administration. Moreover, PURPA did not immediately expand the renewable energy industries, as the cost of energy production from most renewable resources remained high, utilities creatively avoided PURPAs requirements, and some states placed little pressure on their utilities to comply (Joskow, 2001; Kelley, 2008; J. C. Williams, 1997). For example, while R&D programs led to the cost of solar power generation dropping from $1.50 per kilowatt hour (kWh) to $0.35 per kWh by 1988, this cost was still six times higher than the cost of conventionally-generated electricity at the time (J. C. Williams, 1997). With fossil fuel prices falling during the same time period, PURPA payment levels (which were tied to the avoided cost of conventional generation) also fell, slowing growth of solar energy development.[20] Additionally, a large portion of the qualifying facilities under PURPA relied on cogeneration from efficient gas combustion turbines and combine-cycle units that were relatively low-cost, quick to install, and took advantage of declining natural gas prices (Hirsh, 2002).

In the 1990s, major energy policies at the federal and state levels opened up the electricity supply sector to increased competition from non-utility power providers and offered some additional support for the development of renewable energy and energy efficiency. Congress passed the Energy Policy Act of 1992 (EPACT), which created new subsidies for energy efficiency and renewable energy technologies; encouraged states to implement utility "integrated resource planning" with preference given to renewable and demand-side management resources; and paved the way for competition in wholesale power production (Hirsh, 2002; Joskow, 2001). The EPACT, along with subsequent wholesale energy market reforms implemented by the Federal Energy Regulatory Commission, effectively allowed independent wholesale electricity generators (of all types) to supply power to consumers and mandated open-access transmission at reasonable prices across electricity grid infrastructure owned by the major private utilities (Weare, 2003). Hirsh (2002) argues that together PURPA and EPACT significantly undermined the traditional vertically-integrated structure of electricity supply and weakened the justification for the natural monopoly status of power companies, as independent producers demonstrated they could supply cheap power without the need for massive generating units to provide economies of scale. The EPACT also authorized individual states to implement retail competition in the electricity sector, which according to Hirsh (2002, p. 240) "marked the death of the utility consensus" as states restructured (dismantled) vertically-integrated electric

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[20] Williams (1997) notes that the wind industry faired better in the 1980s as technical advances and lower capital costs for turbines allowed wind power production to continue remaining economically competitive even as fossil fuel prices dropped.

utilities.[21] As Kelley (2008) suggests, these acts set the stage for the renewable energy mandates states have since put into place in efforts to reduce carbon emissions from the electricity sector.

By the 2000s, the relationship between energy and the environment had returned to focus amid growing concern over greenhouse gas (GHG) related climate change. While modern scientific research on atmospheric GHG concentrations and associated climate change has been ongoing since the 1960s, this issue gained more widespread public traction after the formation of the Intergovernmental Panel on Climate Change (IPCC) in 1988. With the release of their first assessment in 1990, the IPCC acknowledged the global nature of climate change, and in large part, linked it to GHG emissions from fossil fuel combustion (primarily for electricity generation and transportation). Between 1980 and 2000, scientific literature and the press regularly published reports on the effects of burning fossil fuels and implicated coal-driven electrical generation in particular as culpable for large contributions to atmospheric climate change (French, 2017). Moreover, some researchers suggested that economically-extractable supplies of oil would soon peak (C. J. Campbell & Laherrère, 1998), which sparked calls to diversify America's energy sources. Based on extensive modeling of emissions, climate, and impact scenarios,[22] there is general scientific consensus today that to reduce the likelihood of dangerous anthropogenic interference with climate, policymakers should focus on achieving a 2050 target of reducing GHG emissions to 80% below 1990 levels. This target corresponds to stabilizing atmospheric concentrations of carbon dioxide at 450 parts per million, the quantity estimated to be associated with an approximately 2 degree Celsius (^{o}C) increase in global average temperature.

Recognizing that such climate change mitigation and adaptation will require widespread societal reform, a broad body of scientific research has focused on strategies for achieving emissions stabilization through changes in technology, economies, lifestyle, and policy. Renewable energy sources are viewed as one viable way to reduce anthropogenic emissions of GHG. In the energy context, insights from this body of research suggest that climate change mitigation will require components such as energy efficiency, decarbonizing electricity production (e.g. by switching from fossil to renewable fuels), and subsequently electrifying direct fuel end uses such as transportation (American Physical Society, 2008; Intergovernmental Panel on Climate Change, 2012; Jacobson, 2009; Jones & Kammen, 2011; Pacala & Socolow, 2004; Wei et al., 2013; J. H. Williams et al., 2012). Pacala & Socolow (2004), for example, conceptualize "wedges" of existing available mitigation technologies and actions that could reduce emissions to target levels, including, among others, replacing coal-generated electricity with electricity generated by wind and solar. Moreover, J. H. Williams et al. (2012) conclude that after other emission reduction measures are employed, widespread switching of direct fuel uses (e.g. car gas) to electricity will be necessary to achieve desired levels of mitigation.

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[21] States like California, which faced high retail electricity rates in the 1990s due to expensive investments in nuclear plants and high-priced contracts for qualifying facility power, implemented free market principles and restructured (dismantled) vertically-integrated utilities in the 1990s.While a full discussion of the origins and effects of deregulation in general and California's restructuring (and subsequent energy crisis) in particular is outside the scope of this research, Hirsh (2002), Joskow (2001), and Weare (2003) are excellent resources on these topics.

[22] See Füssel & Klein (2006) for a discussion of the evolution of climate change vulnerability assesstements and Moss et al. (2010) for a chronology of climate change scenario modeling and a description of the current climate change scenarios widely in use.

Given the future climate implications of present-day energy production and consumption, energy has also become a key focus in the sustainability[23] framework of twenty-first century public policy and planning. In the absence of overarching federal action to significantly reduce carbon emissions, state and local governments have taken the lead in setting emission reduction goals and mitigation policies (Kelley, 2008; Lutsey & Sperling, 2008). Various researchers have documented the types of policies and actions undertaken at these levels (e.g. see Rabe, 2004, 2009; Ramseur, 2007). Mitigation policies and actions are generally specific to broad economic sectors, with primary focus on reducing GHG emissions from the greatest contributors—the electricity and transportation sectors—which contributed 29% and 27% of U.S. GHG emissions respectively in 2015 (Lutsey & Sperling, 2008; U.S. EPA, 2015).

In terms of the power sector, Lutsey & Sperling (2008) note that the most widespread action taken by states has been the adoption of renewable portfolio standards (RPS), mandates, and targets designed to increase the percentage of electrical demand supplied with power generated from renewable energy sources. As of 2017, mandatory RPS were in place in 29 states, three U.S. territories, and the District of Columbia (Barbose, 2017), while another eight states and one territory have voluntary renewable energy portfolio goals (Durkay, 2017). Similarly, states have enacted net metering laws, regulation interconnection guidelines, and renewable energy tariffs to support these mandates and goals (Elkind, 2009; Kelley, 2008). Some states have also specifically encouraged small-scale, distributed renewable generation (DG) via carve-outs or multipliers for wholesale DG associated with RPS (Barbose, 2017) and/or behind-the-meter DG incentive programs offering financial incentives for customers to install renewable generating capacity to offset their load (Carley, 2009, 2011).

In addition to broad recognition of the direct environmental consequences of the American energy binge, the 1960s ushered in a backlash on the urban sprawl that was in part facilitated by increasing commodification of energy. The burden urbanization placed on the natural environment was seen as a metropolitan and environmental crisis (Miller, 1987) and the surge of population into the periphery brought with it the very problems suburbanites hoped to escape, including pollution, crime, lack of infrastructure, and traffic. Despite the backlash, Miller (1987) suggests that metropolitan sprawl continued through the 1960s, noting that by 1970 over half of urban residents in the U.S. lived in suburbs. The 1973 energy crisis led to rapid constraints on energy, but Owens (1986) argues that this shock was too abrupt for settlement structures to reflect any real adjustment, yet it did result in a heightened awareness of energy as a factor influencing urban development. Droege (2006) uses the term “energy blindness” to refer to the disregard for energy as a force shaping urbanization that affected urban scholars prior to this period. But the environmental movement and energy crisis shifted the view of energy from an engineering requirement to be satisfied to a key element influencing urban development itself

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[23] Sustainable development essentially seeks to balance environmental protection, economic development, and intergenerational equity (S. Campbell, 1996). However, definitions of sustainability (and/or sustainable development) are vague at best, as illustrated by the imprecise terms in the most frequently cited definition from the 1987 Brundtland Commission’s “Our Common Future” report: “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Jepson, 2001, p. 8). Sustainability remains a formidable challenge given that its objectives are often inherently contradictory resulting in conflicts that block their integration (Berke, 2002; S. Campbell, 1996; Godschalk, 2004). Melosi (1987) views the debate over America’s energy future in a similar context as a struggle between energy, economy, and environment, with efforts to address one crisis perceived as the cause of crises for the other two.

(Burchell & Listokin, 1982; Droege, 2006). Much scholarly research has focused on transportation-related energy consumption and its influence on urban form. However, scholars have also called for a focus on how energy resources and systems themselves have influenced past patterns of development (Burchell & Listokin, 1982; Melosi, 1990; Nye, 1994; S. Owens & Rickaby, 1983; Platt, 1987, 1991; Rose & Clark, 1979; Rosenberg, 1998; Viehe, 1981) and may influence patterns of urbanization in the future (Burchell & Listokin, 1982; Carroll & Udell, 1982; Droege, 2006; Morris, 1982; Susan E. Owens, 1986).

While government policies today specifically mandate and incentivize increased generation of electricity from renewable sources, these sources remain a small (but growing) fraction of total energy supply in America (Figure 2). Nevertheless, they have fostered debate over the potential for another major primary energy source transition in the United States to renewable resources. As of 2017, renewable energy sources accounted for approximately 11% of total U.S. energy consumption and 17% of total U.S. electricity generation (U.S. Energy Information Administration, 2018c). The fraction is higher in some states, however. For example, 76% of Oregon's net electricity generation in 2017 came from renewable resources, primarily hydroelectricity and wind (U.S. Energy Information Administration, 2018e), and the U.S. Energy Information Administration (2018d) cited 10 states where wind and solar production in 2017 made up at least 20% of the states' total in-state electricity production including: Iowa, Kansas, Oklahoma, South Dakota, North Dakota, Vermont, California, Maine, Colorado, and Minnesota.

These levels of renewable energy production are considerable increases over the levels seen two decades ago, leading to suggestions of a bourgeoning transition. Much more than just a question of what resources should be used to supply energy, the debate around an alternative energy future also focuses on the structure of the social and technical systems that produce and sustain economic and physical growth as broader considerations (e.g. Lovins, 1976). The possibility of a technological and social shift from centralized, top-down systems to increasingly decentralized, local systems is one key focus of this discussion. Questions about the potential urban development and environmental implications of a broader transition to renewables also remain. Droege (2006) notes that during the resurgence of fossil fuel usage and energy consumption in the 1980s and 90s there was a brief decline in the study of energy influences on urbanization. But since the millennium, amid the implications of climate change and calls for a transition from conventional to renewable electricity sources, a diversity of urban planning efforts have focused on making development more "sustainable," with an emphasis on energy. For example, these efforts have included ecological planning, low-impact site design (LID), Leadership in Energy and Environmental Design (LEED), eco-cities, ecological footprints, and smart growth. At the same time, Williams (1997, p. 337) cites the fact that "making human settlement patterns more flexible became, for many solar champions, a crucial social benefit of harnessing the sun's energy."

The debate over alternative energy futures continues today.

III. The Next Transition?

The American energy history traced herein has shown that factors such as technology, price, consumer preference, and environmental impacts, among others, can spur shifts in energy sources. Factors facing society today portend that another shift, one towards low-carbon energy sources, may occur. Though America's energy supply has always come from a mix of resources, the country has transitioned through energy regimes largely dominated by wood, water, and wind, followed by coal, and then oil, natural gas, and electricity. Sachs (2015) suggests that once technologies and infrastructures associated with a particular dominant energy source are in place, that energy system acquires a "technological momentum," and continued use of the energy source may appear inevitable. Yet, he concludes that just as human choices through history have established our existing energy system, human choices, influenced by factors such as resource availability and environmental awareness, have the potential to push society toward more serious energy shifts in the twenty-first century. According Monstadt (2009), socio-ecological problems like climate change, air and water pollution, and resource shortages can only be tackled through the transition of existing infrastructure systems. As early as the 1980s, Tarr and Lamperes (1981) proclaimed the United States to be at the beginning of just such a transition in energy systems, from an overwhelming dependence on cheap and abundant supplies of oil and natural gas, to a variety of renewable energy sources. Twenty years later, Bridge et al. (2013) argue that there is now widespread recognition within the interdisciplinary field of energy studies that climate change, energy security, and the depletion of conventional oil reserves are re-working established patterns and scales of energy supply, distribution, and consumption. Furthermore, in the case of electricity in particular, numerous scholars suggest that though the age of massive, centralized power systems is not over, emerging within the interstices of these systems are smaller, distributed renewable energy technologies that forecast a continuing relative shift from a centralized to an increasingly decentralized future for electricity generation (Jiusto, 2009; Bridge et al., 2013; Carley & Andrews, 2012). As has been the case with historical energy transitions, the nature of the energy resources that dominate any new energy regime (their geographic concentration, energy density, etc.), the technologies developed to extract those resources, and the infrastructure systems through which their power is consumed, will in turn shift constraints on the location and spatial structure of urban growth, as well as change the location and nature of environmental effects associated with energy production and consumption.

Theories across a number of disciplines help provide insight into the potential for a transition to renewable energy sources to occur. On the one hand, technology and innovation studies often emphasize that enormous sunk costs in system components, as well as related scientific knowledge bases, engineering routines, user practices, and regulatory institutions, which create significant inertia and path dependency in large infrastructure systems. Such path dependency can present considerable barriers to radical innovation and relegate change in infrastructure systems to incremental refinement of existing solutions (Monstadt, 2009). At the same time, this inertia may in fact breed change. Panarchy Theory, for example, explains the process by which natural, social, and technological systems undergo transformation as a cyclical function of four phases: exploitation, conservation, release, and reorganization (Gunderson & Holling, 2002). While the exploitation phase is characterized by rapid growth, eventually competition gives way to domination by a few and the internal controls of the system increase to the point at which it becomes rigid and inflexible, resilience diminishes, and the potential for change increases (Gunderson & Holling, 2002). In this rigid state, argue Gunderson and Holling (2002), disturbance of the system can trigger reorganization and potentially transformative change. Viewing the existing centralized electrical institution as having reached a state of high inflexibility and climate change, environmental awareness, and the perceived need for energy security as disturbances to this system, Panarchy Theory suggests that the potential for transformative reorganization exists. Similarly, Farrell & Brandt (2006) suggest that the path of technological change is non-linear and can often be altered significantly by decisions made in the times of crisis or disturbance to the status quo.

While Panarchy Theory implies that change in the existing system is plausible, other theories provide insight into the spatial form that such change might take. Historically, Americans have long associated the concept of progress with expansion of human knowledge about, and power over, nature, which has led to what Marx (1967) and Nye (1994) describe as the "technological sublime." This concept represents a cultural view in which "the awe and reverence once reserved for the Deity and later bestowed upon the visible landscape is directed toward technology, or rather the technological conquest of matter" (Marx, 1967, p. 197). Since the 1820s, numerous technologies associated with the production and consumption of energy have been viewed through the lens of the technological sublime, including early watermills, coal-powered steam engines and factories, hydroelectric dams and other power plants, electric lighting, and nuclear power (Nye, 1994). Through their physical or numerical scale and their potential to transform society, these technologies engendered sublime feelings of awe, insignificance, pleasure, and even fear related to man's ability to construct an infinite world (Nye, 1994). Today renewable resources, in particular solar, offer the opportunity to generate power along a spectrum of scales, from large, centralized facilities down to individual distributed units on rooftops. While the existing energy system is highly centralized, many scholars predict future growth in decentralized, renewable energy generation (Alanne & Saari, 2006; Burton & Hubacek, 2007; Klose, Kofluk, Lehrke, & Rubner, 2010; Wolsink, 2012; Zahedi, 1996). A transition to renewable energy technologies can be viewed in part as a new form of the technological sublime, facilitating continued human progress in the face of climate change and finite fossil fuels. However, the technological sublime principally seems to apply to large, complex technologies set against a discontinuous backdrop of nature. This implies that the technological sublime viewpoint would encourage massive, centralized renewable energy installations as opposed to distributed, small-scale renewable energy applications. Kammen and Dove (1997) capture this sentiment in suggesting that energy research has disproportionately focused on complex technologies and larger centralized power facilities instead of simpler technologies and local consumption because research into the latter is seen as mundane and not amounting to scientific progress. However, they suggest that a focus on "mundane science" often arises in times of crisis and leads to change in the stats quo (Kammen & Dove, 1997).

Although economic, regulatory, technical, and institutional barriers to distributed generation remain (Black & Veatch, 2009; Elkind, 2009; Lopes, Hatziargyriou, Mutale, Djapic, & Jenkins, 2007; Martin, 2009; Pepermans, Driesen, Haeseldonckx, Belmans, & D'haeseleer, 2005; Russell & Weissman, 2012), they are hardly insurmountable and theoretical implications from various disciplines suggest a transition to more distributed energy supply could occur. (Carley & Andrews, 2012) specifically suggest that continued technological inertia of the centralized electrical system is not inevitable and could be disrupted by distributed renewable energy technologies. Theories such as Amory Lovins' (1976) vision of the soft energy path suggest a strong potential for transition to distributed renewable energy generation. The soft path emphasizes transitioning to a distributed energy supply structure with diverse, renewable technologies that are already proven and which would level the energy-access playing field by facilitating more bottom-up, democratic control of the system (Lovins, 1976). Such a shift to localized, bottom-up energy generation fits into the objectives of what Professor of Environmental Politics, David Schlosberg, calls "the new environmentalism of everyday life." He describes this movement as an extension of a trend towards regaining community power that has been occurring since the 1960s (Schlosberg, 2013). This new environmental movement—exemplified by decentralized energy generation, slow food, and localized crafting/making—focuses on restructuring the flows of materials through communities to shift the balance of power derived by controlling these flows (Schlosberg, 2013). Similarly, distributed renewable energy generation also has been incorporated into planning movements and regulations associated with the "sustainability" paradigm including LEED and smart growth, which are facilitating increases in the amount of power supplied at the building and community scale (Straka, 2002). Moreover, Carley and Andrews (2012) suggest a number of trends point to a shift towards increasing decentralization of the electricity system, including rising resistance to and cost/timeframes for constructing transmission lines; recognition of the energy security benefits of diversification of generating sources and locations; ability of distributed generation to match demand and scale up quickly; and government mandates and incentives specifically for distributed renewable energy generation.

A. Potential Responses of Urban Development and Environmental Effects

The burgeoning transition to an energy regime dominated by renewable primary energy sources and the infrastructure systems used to supply electric power from those sources, whether centralized, decentralized, or a combination of the two, can be expected to, in turn, shift constraints on the location and spatial structure of urban development as well as change the location and nature of environmental effects associated with energy production. In their book *Sustainable Energy Landscapes*, Stremke & van den Dobbelsteen (2013, p. 3) exclaim "There is no doubt that the assimilation, conversion, storage, and transport of renewable energy will be one of the most important land uses of the twenty-first century." They argue that akin to the change in the built environment attributed to the introduction of the automobile in the twentieth century, a transition to renewable sources of energy will affect the spatial organization of the larger physical environment across the world, including both urban and rural landscapes. Yet as Owens (1986) cautions: while there is a sense that future changes in the energy system are likely to influence regional development and urban structure, there is considerable uncertainty about how and to what extent. This largely remains the case today. For example, Jiusto (2009) describes the social, technological, and geographical implications of a low-carbon energy transition as likely to be significant but also hard to imagine. Contemporary work on potential low-carbon energy transitions has paid only limited attention to questions of scale and space (Bridge et al., 2013). Moreover, discussion regarding future energy options rarely frame scenarios in terms of environmental criteria other than carbon mitigation potential (Carley & Andrews, 2012). Thus, the ways in which patterns of development and environmental impacts might evolve in response to future changes in the energy system remain abstract.

As has occurred with past energy transitions, changing patterns of energy production in the future may affect regional development, employment opportunities, and settlement patterns (Owens, 1981). For example, Howard, Wadsworth, Whitaker, Hughes, & Bunce (2009) note that landscapes dedicated to fossil fuel extraction are today scrutinized by policymakers for ways in which their carbon-intensive character might be foreclosed, mitigated, or offset, while locations which provide opportunities for the generation of renewable power gain a new source of potential value and are targeted for commercial development. With renewable resources such as sunlight and wind being at once both ubiquitous across the landscape and concentrated in certain areas, targeted locations can include remote settings such as uplands (for wind farms), deserts (for solar farms), and open ocean passages (for wind and tidal power), as well as urban environments (for rooftop PV and energy from waste) (Howard et al., 2009). In 2014, the automaker Tesla, for instance, specifically included space for hundreds of megawatts (MW) of solar and wind power as a requirement when choosing where to locate its massive battery factory (Wesoff, 2014). The company eventually selected a site outside of Reno, Nevada, in part to take advantage of its solar resources. Other companies like Apple and the data center company Switch, have followed suit, constructing massive, energy-intensive data centers with their own renewable energy supplies nearby (Hidaigo, 2016; Sverdlik, 2017). In fact, Apple has committed to powering its operations entirely by renewable energy and had reached 93% percent renewable power worldwide as of 2016 (Sverdlik, 2017).

As the production of energy shifts to such locations, history suggests they will also see increased employment, population, and urban growth. According to (Ballaban, 2016), in Reno these facilities have created hundreds of thousands of jobs, tripled the city's normal growth rate, and led to an anticipated 7.1% increase in population by 2019, while the rest of the country has seen less than one percent population growth on average for more than a decade. Community officials, seeking to lure industries to relocate or construct new facilities within their jurisdiction, have typically engaged in "the race to the bottom" by seeking to have the least restrictive environmental regulations in order to attract business and the revenue it brings (Pasqualetti & Brown, 2014). Today, with more companies seeking renewable power, one can imagine localities with concentrated renewable resources in a "race to the top" to attract business and industries. This is beginning to play out in Nevada, where Switch is now planning to build the largest PV plant in the United States, and its CEO has exclaimed, "Nevada enjoys the best solar window in the nation and so we Nevadans should not only be using solar for ourselves, but exporting it throughout the Western United States to create new jobs, tax revenue, economic diversification and raise energy independence" (Misbrener, 2018).

In addition to patterns of settlement, the spatial structure of cities is also likely to respond to changes in the energy system (Owens, 1986). Historically, the form of cities has, to a certain degree, reflected energy constraints or the lack there of. Pasqualetti & Brown (2014) provide a comparative example of this suggesting that in older cities, such as London, population densities are higher and urban form more compact than in relatively new cities like Phoenix because older cities took shape before dominant use of the most flexible and convenient forms of energy and transportation—electricity and automobiles. According to Bridge et al. (2013), at the urban scale, the low-carbon energy transition is challenging long-standing assumptions about city spatial form, the density of settlement, and even building design. Different low-carbon energy sources and the scale at which associated power generating technologies are deployed will impose unique constraints on spatial structure and may have very different implications for urban form (Owens, 1979, 1986). As Owens (1986, p. 12) suggests, "An electrified society relying on centralized generation of electricity from nuclear power would be subject to different spatial constraints from a society meeting its energy needs by exploiting renewable energy sources on the scale of the individual household or neighborhood." Owens (1986) goes on to argue that the latter would almost certainly require some decrease in urban density and/or dispersed, small-scale settlements. On the other hand, Burchell and Listokin (1982), question whether site specific solar installations will reduce immediate energy cost pressures enough to allow movement away from metropolitan locations. Given these implications, Bridge et al. (2013) make a case for examining energy transitions as a geographical process involving the reconfiguration of current patterns and scales of economic and social activities, including urban development. Yet there has been limited research to date on the potential responses of urban form to energy system transitions and associated changes in development constraints.

This lack of attention to potential changes in urban form may stem from the fact that such changes are likely to occur over extended time horizons given the entrenched spatial structure of the existing built environment and the long lifetime of existing infrastructure systems. The built environment, once established, is a relatively permanent feature (Owens & Rickaby, 1983), and energy infrastructures tend to have long expected lifetimes, restricting what changes might be possible in the short to medium term (Owens, 1986). While growth and redevelopment present opportunities for modification to the built environment, Owens (1979) suggests such changes will be gradual, incremental, and take time to have a significant impact. Moreover, while energy transitions may facilitate changes in urban settlement location and structure by altering constraints on these processes, individual choices based on numerous social, economic, political, and technological factors are the true basis for such changes (Melosi, 1985; Owens, 1986; Pasqualetti & Brown, 2014; Sachs, 2015; J. C. Williams, 1997). Owens (1986) suggests that changes in urban form may only result if energy system transitions are accompanied by other social and political changes. Yet, we may be in the midst of such social and political shifts with Schlosberg's (2013) new environmentalism and policy mandates for low-carbon DG, for example. Given the burgeoning renewable energy transition, the connection between energy and land use, and the view that incremental change over time can produce significant shifts in the built environment, planners should seek to understand the potential responses of urban form to changes in the energy system before they occur.

The potential environmental implications of the changing nature and patterns of energy production and urbanization are also important considerations. While society has a tendency to perceive each new dominant energy resource through history as a great panacea (J. C. Williams, 1997), there are always going to be environmental costs to energy production. (Cook, 1976) warned that despite our ability to find, use, and measure energy, we were far from being able to foresee the (possibly irreversible) environmental and social consequences of energy production and use – this remains the case more than 40 years later. It is critical to discern the possible environmental impacts of technological systems and whether these impacts can or will change as the system evolves (Melosi, 1990). While development of various renewable, low-carbon energy resources may help to mitigate climate change, it has also given rise to concerns over land use, water use, aesthetics, and even air pollution (e.g. when burning biomass resources). Sachs (2015) notes that some communities have already rejected wind farms on aesthetic grounds and that solar panel production creates toxic pollution. Others suggest a transition to low-carbon energy sources means that energy will again become a major driver in land cover change (Dale et al., 2011; Howard et al., 2009; Kiesecker & Naugle, 2017; Nadaï & van der Horst, 2010). As Kiesecker and Naugle (2017) point out, while renewables have great environmental appeal, the land cover change caused by their development can also fragment habitats, interfere with wildlife migration and natural flood regimes, and serve as a conduit for nonnative species. In terms of water use, Pasqualetti and Brown (2014) suggest the water/energy nexus has become a particularly important environmental consideration for future renewable energy development, especially in arid areas.

IV. Conclusion

This chapter has traced historical energy transitions and their influence on settlement locations, forms of urban development, and environmental effects in the U.S. through time. It concludes by considering the potential for another transition to renewable energy sources. Through this work, the effects of shifting energy constraints on the built environment become apparent across many spatial scales. At the building scale, the evolution of energy sources influenced the design of the factory itself. Facilities morphed from small mills limited in size by the power flowing from the adjacent waterway; to large, multi-story buildings designed such that ground floor, coal-based steam power could drive overhead belting systems in stacked workspaces; to today's single-story, horizontally expansive buildings powered by electricity (Nye, 1994; J. C. Williams, 1997). At the regional scale, different dominant energy resources through time served to attract settlement and growth in varying regions. While at the city scale, the evolution of energy choices has had both concentrating and expanding influences on urban form. For example, the transition from water to coal-based power presented the opportunity for factories to move into cities attracting population growth in those cities, while diffuse oil resources in the Los Angeles Basin influenced diffuse urban growth across the area. With today's massive, centralized electrical grid extending across the nation, power is widely accessible, leaving few vestigial restraints on urbanization. However, this system is largely powered by fossil fuels. In the face of climate change and the perceived need for energy security, there have been increasing calls to shift to diverse renewable primary energy sources. Renewable resources offer the opportunity to generate power from large, centralized facilities down to individual distributed generation units. Thus, Bridge et al. (2013) suggest that the geographies of a low carbon energy future are not yet determined and that a range of divergent potential geographical futures are in play. While uncertainty remains over the exact nature of a low-carbon energy future in America, history suggests that a transition in the dominant energy sources used to power the country will present new choices about where and how to urbanize, as well as alter the direct and indirect environmental effects of our energy system. Given these significant implications, research based on future energy scenarios, and in particular, their potential to influence urban development and environmental effects, is critical to help policymakers and stakeholders make informed evaluations of the energy pathways available to society.

Chapter 3. Regional Land, Water, and Air Pollutant Emission Effects of Low-carbon Power System Scenarios for Western North America

I. Introduction

Efforts to mitigate climate change by reducing anthropogenic GHG emissions are already beginning to re-work established patterns and scales of energy supply, distribution, and consumption (Bridge et al., 2013). Yet without careful planning, these efforts could result in other significant, unintended environmental consequences. The historical and theoretical analysis presented in Chapter 2 suggests that despite carbon emission reduction benefits, the burgeoning transition to a low-carbon energy regime is likely to change the nature and location of the environmental effects associated with society's energy systems. Chapter 2 concludes that informed energy and environmental planning will require foresight into the potential for future energy scenarios to directly impact natural resources. Heeding that conclusion, in this chapter, I present a novel simulation and assessment approach to evaluate, over time and across the landscape, the nature and distribution of potential direct impacts to natural resources under various future low-carbon energy system scenarios. I contend that approaches such as this, and the associated findings, are critical to making informed assessments of the various low-carbon energy pathways available to society and to avoiding unintended environmental consequences from energy infrastructure transitions.

There is general scientific consensus that to reduce the likelihood of catastrophic anthropogenic interference with climate, policymakers should focus on achieving a 2050 target of reducing GHG emissions to approximately 80% below 1990 levels to stabilize atmospheric concentrations of carbon dioxide at around 450 parts per million, the quantity estimated to be associated with an approximately 2^{o}C increase in global average temperature (Intergovernmental Panel on Climate Change, 2014). Mitigation policies and actions to date have primarily focused on reducing GHG emissions from the greatest contributors—the electricity and transportation sectors. Research suggests that achieving target levels of GHG reductions from the electricity sector will require energy efficiency advances, decarbonizing electricity production (e.g. by switching from fossil to renewable fuels), and subsequently electrifying direct end uses of energy such as transportation (American Physical Society, 2008; Intergovernmental Panel on Climate Change, 2012; Jacobson, 2009; Jones & Kammen, 2011; Pacala & Socolow, 2004; Wei et al., 2013; J. H. Williams et al., 2012). To fully evaluate policies intended to promote significant GHG reductions from the electric power sector, policymakers must understand the broader environmental implications of various potential low-carbon energy pathways.

The simulation and assessment method advanced in this chapter examines the spatial and temporal distribution of air pollution, water consumption, and land conversion directly associated with operation and expansion of the electrical grid under various realistic electrical power system scenarios designed to limit regional carbon emissions from North America's Western Electricity Coordinating Council (WECC) region (Figure 3). The electric power system scenarios analyzed in this approach are produced using the SWITCH[24] model, a realistic

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[24] SWITCH is a loose acronym for Solar, Wind, Hydro and Conventional Generation and Transmission Investment.

electrical capacity expansion and operation model for western North America. I explore the temporal and spatial distribution of these environmental effects across six energy system scenarios designed to meet projected increases in demand while limiting regional carbon dioxide (CO_2) emissions to below “2^{o}C levels” (specifically to 40 megatonnes (Mt) CO_2 year^{-1} or 86% below 1990 emission levels) by 2050. These “decarbonization” scenarios include various future policy, economic, and resource conditions, and I compare their environmental effects to those of a separate BAU scenario modeled in SWITCH. The SWITCH model scenarios simulate the least-cost evolution and operation of the WECC power system out to 2050 under the specified policy, economic, and resource constraints as well as the CO_2 emission constraint. Using power production and installed capacity outputs from these SWITCH scenarios, I quantify the associated environmental effects through time as well as at a high spatial resolution across western North America.

I find that air pollutant emissions, water consumption, and land use conversion vary across the decarbonization scenarios by as much as 108,000 annual tonnes (t), 145×10^9 annual liters (L), and 491,500 cumulative square hectares (ha^2), respectively. These results confirm that different policy mechanisms and technologies employed to shift to a low-carbon electrical sector can be expected to shift the magnitude and distribution of regional environmental effects. In particular, these results suggest vast amounts of land are likely to be necessary to support low-carbon energy generation and transmission infrastructure under all scenarios evaluated, and that the localized land use conversion, water consumption, and air pollution effects experienced across the WECC region will depend on the low-carbon technologies and policies implemented. The method presented herein, which forecasts potential environmental implications of electrical grid expansion and operation under various low-carbon scenarios across time, space, and multiple environmental resources, can be used to provide decision makers with robust information to evaluate potential environmental tradeoffs and risks of new energy policies and pathways before they are implemented.

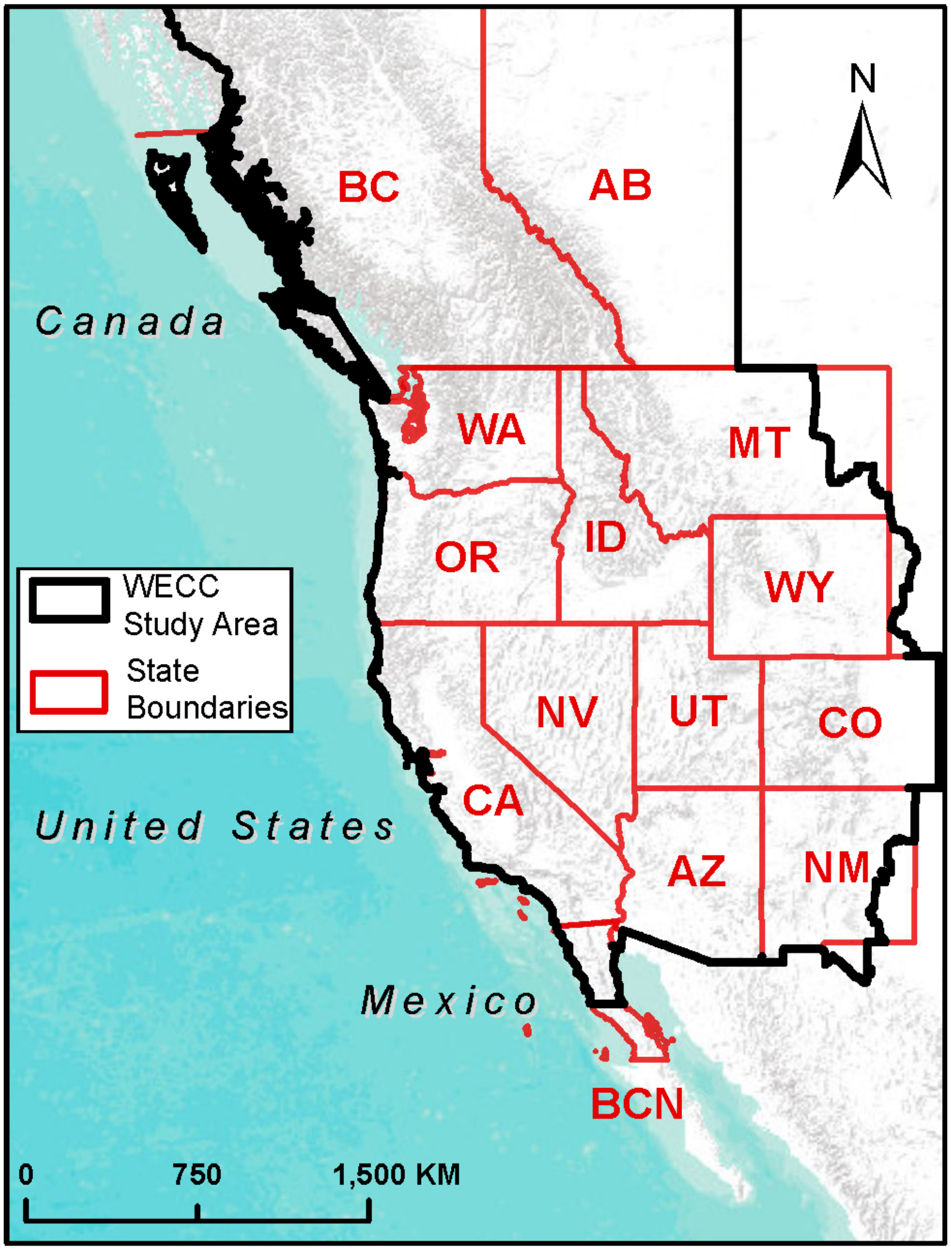

Figure 3. Western Electricity Coordinating Council study region and associated U.S. states, Canadian provinces, and Mexican states. (Base map data source: ESRI, USGS, NOAA)

Electric generators are the largest stationary emitters of CO_2 in the United States, with the electricity sector contributing 28.4% of U.S. GHG emissions in 2016 (U.S. EPA, 2017). Previous work suggests that reducing electricity sector emissions is critical to achieving the deep carbon reduction targets necessary to mitigate climate change (e.g. Wei et al., 2013; J. H. Williams et al., 2012; Kiesecker & Naugle, 2017). National and international policies aimed at decarbonizing the electricity sector focus in large part on transitioning power production to low- or no-carbon options such as renewable energy technologies or fossil fuel facilities with carbon capture and storage (CCS) infrastructure. Yet these technologies have diverse economic costs, operating characteristics, and environmental effects. As such, policies designed to shift regional energy systems to low-carbon technologies may have significant environmental implications, notwithstanding beneficial reductions in global carbon emissions. Despite this potential, the local land, water, and air quality consequences of climate mitigation policies effecting regional energy systems have, to date, received only limited examination (Howells et al., 2013; Kiesecker & Naugle, 2017; Wallis et al., 2014). The method presented herein addresses this by integrating realistic, regional energy capacity expansion and operation modeling with multiple environmental impact assessment models to temporally and spatially characterize the air pollutant emissions, water consumption, and land use conversion associated with various electrical system decarbonization scenarios for North America's WECC region.

Considerable research has focused on characterizing and comparing the potential land, water, and air quality impacts associated with generating energy from specific renewable or conventional technologies. I present a discussion of the existing literature quantifying these impacts for various generation technologies in Section II.C of this chapter. While these studies are informative, decision makers focus not on selecting "the best" technologies, but on implementing technology policies that meet emission targets at the lowest cost to society (Fischer, Torvanger, Shrivastava, Sterner, & Stigson, 2012). As Weisser (2007) points out, comparisons of impacts among generating options can help identify their relative merits but do not capture the degree to which the options, and their associated impacts, are true alternatives based on economic competitiveness, policy conditions, and their performance characteristics in a grid system. Thus, evaluating the complex environmental effects of carbon reduction policies requires an examination of their influence on the deployment and operation of renewable and conventional generators in an interconnected grid system. Yet, relatively few studies have captured these interdependences.

Those studies that have explored U.S. carbon reduction policy scenarios and associated environmental impacts using energy-economic optimization models primarily focus on a single environmental effect, such as water use (Baker, Strzepek, Farmer, & Schlosser, 2014; Chandel, Pratson, & Jackson, 2011; Clemmer, Rogers, Sattler, Macknick, & Mai, 2013; Macknick, Sattler, Averyt, Clemmer, & Rogers, 2012), air pollution (Blumsack & Xu, 2011), or land use (Kiesecker & Naugle, 2017; McDonald et al., 2009) as opposed to effects across multiple resources. An exception to this is Arent et al. (2014) who describe water use, land use, carbon emission, and source material implications for future low carbon energy system scenarios modeled as part of the Renewable Electricity Futures study (National Renewable Energy Laboratory, 2014). However, they report these implications at a national level. Howells et al. (2013) similarly develop a multi-resource assessment method evaluating climate, land-use, energy, and water to evaluate effects at a national scale and apply it to the Republic of Mauritius. Other studies focus on life cycle as opposed to direct environmental effects of energy system scenarios. Laurent and Espinosa (2015), conduct a back cast of the environmental implications of shifts in energy generation from 1980-2011 across 199 countries using life cycle analysis for a spectrum of environmental effects. They find variation in trends across countries as well as examples of impact burden shifting through time. While not examining future energy scenarios in their analysis per se, they suggest the need for integrating quantitative assessments of all relevant environmental impacts associated with future energy systems to identify the most sustainable energy pathways.

The results of these studies suggest that climate policies will have complex effects on electricity generation choices and associated environmental implications. According to J. Macknick, Newmark, Heath, & Hallett (2012, p. 1), “a transition to a less carbon intensive electricity sector could result in either an increase or a decrease in water use, depending on the choice of technologies and cooling systems employed” since some generation technologies with low GHG emissions have relatively high water consumption per unit energy produced while others have both low emissions and water consumption. Similarly, Chandel et al. (2011) use a modified version of the U.S. Energy Information Administration’s (EIA’s) National Energy Modeling System (NEMS) to evaluate the effect of carbon pricing on water withdrawal and consumption for energy generation out to the year 2030. They find that increasing the price of carbon reduces water withdrawals by the electricity sector 2–14% relative to a BAU scenario but that at high carbon prices, retrofitting fossil fuel plants to capture CO_2 increases water consumption 14% above BAU (Chandel et al., 2011). Baker et al. (2014) find that the future renewable portfolio scenarios they examine generally lead to overall reductions in water use, but that in certain geographic regions, water consumption increased with respect to nonrenewable scenarios. McDonald et al. (2009) explore the total new land area and habitat types impacted by energy generation in 2030 under various cap and trade scenarios modeled in NEMS and find greater reductions in CO_2 emissions to be associated with more new area affected by energy production, although they conclude the magnitude of increase is highly policy specific. In another example, Blumsack and Xu (2011) conduct a scenario analysis of future electric generation investment and dispatch in the Western United States to 2030 to examine the air pollutant emission effects of incremental wind energy investments beyond existing renewable penetration targets. They find that the introduction of 1GW of wind energy in certain locations can counter intuitively increase WECC emissions of nitrogen oxides and sulfur dioxide as a result of the way in which generation sources are scheduled and dispatched in regional electricity markets.

Adding to and expanding upon this body of research, I base this analysis on numerous scenarios representing the potential future evolution and operation of the WECC power system out to 2050 and use the outputs from those scenarios to quantify multiple environmental effects through time as well as at high spatial resolution across western North America. I analyze the environmental effects of a power system BAU reference scenario and six decarbonization scenarios that achieve the same deep carbon reduction target (40 Mt CO_2 year^{-1} by 2050) for the WECC region under different policy, economic, and resource conditions. I find that by 2050, the decarbonization scenarios evaluated all confer benefits in terms of reduced regional water consumption and air pollutant emissions relative to BAU, but require significantly more land conversion. However, the results also show that the magnitude of these environmental benefits and impacts varies across the decarbonization scenarios. Similarly, the results show large spatial variation in the level of these impacts across the WECC study region, both within and among scenarios. These results suggest that comparative analysis of the environmental effects of various energy technology policy scenarios is critical to avoiding unnecessary or inequitable environmental consequences.

While this analysis focuses on western North America, the context is globally relevant. The top three carbon emitting regions worldwide in 2013 were China, the United States, and the European Union—together accounting for over 55% of total global CO_2 emissions (Olivier, Janssens-Maenhout, Muntean, & Peters, 2014). Clearly, climate mitigation will require a global effort. Recognizing this, parties at the United Nation’s climate change discussions have agreed that in the absence of a binding agreement to decrease carbon emissions, atmospheric CO_2 levels should be constrained to limit global temperature rise to 2°C (Lincoln, 2012). The route to this objective has been left to individual nations to decide, but with electricity generation generally considered central to minimizing CO_2 emissions, many nations have placed an emphasis on transitioning to low-carbon power sources (Bridge et al., 2013; Destouni & Frank, 2010; Hedberg, Kullander, & Frank, 2010; Lincoln, 2012). The Energy Committee of the Royal Swedish Academy of Sciences predicts that by the year 2050, electricity will be the major energy carrier, its production increasing globally by as much as 125% to 45,000 terawatt hours with renewable energy sources supplying an estimated 50% (Destouni & Frank, 2010). Regardless of where in the world they are utilized, energy technologies that reduce carbon emissions may cause other environmental effects and public assessment of the tradeoffs is needed before broad deployment (Fischer et al., 2012).

The decarbonization scenarios analyzed herein are intended to illustrate a range of transition situations that could occur in regions across the globe, such as replacement of other fossil fuels by natural gas, policy mandates for high percentages of electricity generation from renewable sources, declining solar costs leading to widespread deployment of large-scale solar resources, increased implementation of small-scale solar DG, and decreased hydropower production (e.g. due to a drought). Thus, while this research focuses on a western North American study region, the methods are broadly applicable and the conclusions provide valuable insight for other locations evaluating similar potential energy pathways.

II. Methods

The scenarios evaluated in this analysis are modeled in SWITCH[25]—a renewable resource, electrical capacity-planning, and dispatch (operation) model designed to simulate electrical system expansion and operation through 2050 (Fripp, 2012; Nelson et al., 2012). I examine a BAU scenario and six decarbonization scenarios designed to reduce WECC-wide CO_2 emissions to 40 Mt CO_2 yr^{-1} (14% of 1990 levels) by 2050.[26] Based on energy technology investment and operation decisions simulated in SWITCH, I calculate environmental impact factors from estimates in the literature and model quantities of nitrogen oxides (NO_x), sulfur oxides (SO_x), and 10 and 2.5 micron particulate matter (PM_{10} and $PM_{2.5}$) air pollution, water consumption, and land use conversion through time and across the study region.

My analysis focuses on the WECC region (Figure 3), which extends from Canada to Mexico and includes the Canadian provinces of Alberta and British Columbia, the Mexican State of Baja Mexico Norte, and all or portions of 14 western U.S. states. The WECC itself is a non-profit corporation that exists to assure a reliable electric system in the geographic area known as the Western Interconnection, and it has delegated authority from the North American Electric Reliability Corporation (NERC) to create, monitor, and enforce reliability standards in the region (Western Electricity Coordinating Council, 2015).

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[25] The version of SWITCH used to model the scenarios evaluated in this analysis is described in detail in Nelson et al. (2014). The complete model formulation can be found at http://rael.berkeley.edu/switch.

[26] These scenarios were designed for a California Energy Commission study investigating the evolution of the WECC power system in the context of aggressive decarbonization by Nelson et al. (2014).

A. The SWITCH Model

The SWITCH model combines the capabilities of electrical system capacity expansion and hourly operational models to determine least-cost investment in renewable and conventional generation capacity, transmission, and storage, while explicitly accounting for the hourly variability of intermittent renewable resources and electricity loads (Nelson et al., 2012). SWITCH was developed at the University of California (UC), Berkeley (Fripp, 2012) and continues to be expanded and maintained by the Renewable and Appropriate Energy Laboratory (RAEL) at UC Berkeley (Mileva, 2013; Nelson et al., 2012; Wei et al., 2013). The version of SWITCH used in this analysis is designed for the synchronous NERC Western Interconnection (the WECC region). Within this region, the model is designed to simulate electricity demand, generation, storage, and transmission at a finer spatial resolution of 50 distinct load areas (Figure 4). Little electricity is moved between NERC interconnections and thus, the WECC system is modeled as a self-contained system in the SWITCH model.

As described by Nelson et al. (2014), the SWITCH model is formulated as a linear optimization program that minimizes the system-wide net present value of supplying forecasted electrical demand between 2013 and 2050, subject to operational, reliability, and policy constraints. The model can build and/or operate 57 different renewable or conventional generation or storage technologies and transmission infrastructure. The model must satisfy hourly demand and capacity reserve requirements, meet the overall carbon reduction target and additional policy constraints, and conform to generator, storage, and transmission capacity limits. Model inputs include constraints, each technology's operational characteristics, and the capital, operational, maintenance, and fuel costs for different projects. Based on these inputs, SWITCH simultaneously optimizes both investment decisions—those regarding installation of new generation, transmission, and storage infrastructure—as well as dispatch decisions—those regarding the operation of existing and new generation, storage, and transmission capacity—to minimize the total net present cost of the power system. The model treats the transmission system as a generic transportation network rather than simulating physical power flow so transmission capacity is constrained based on the thermal limits of transmission lines (Nelson et al., 2013).

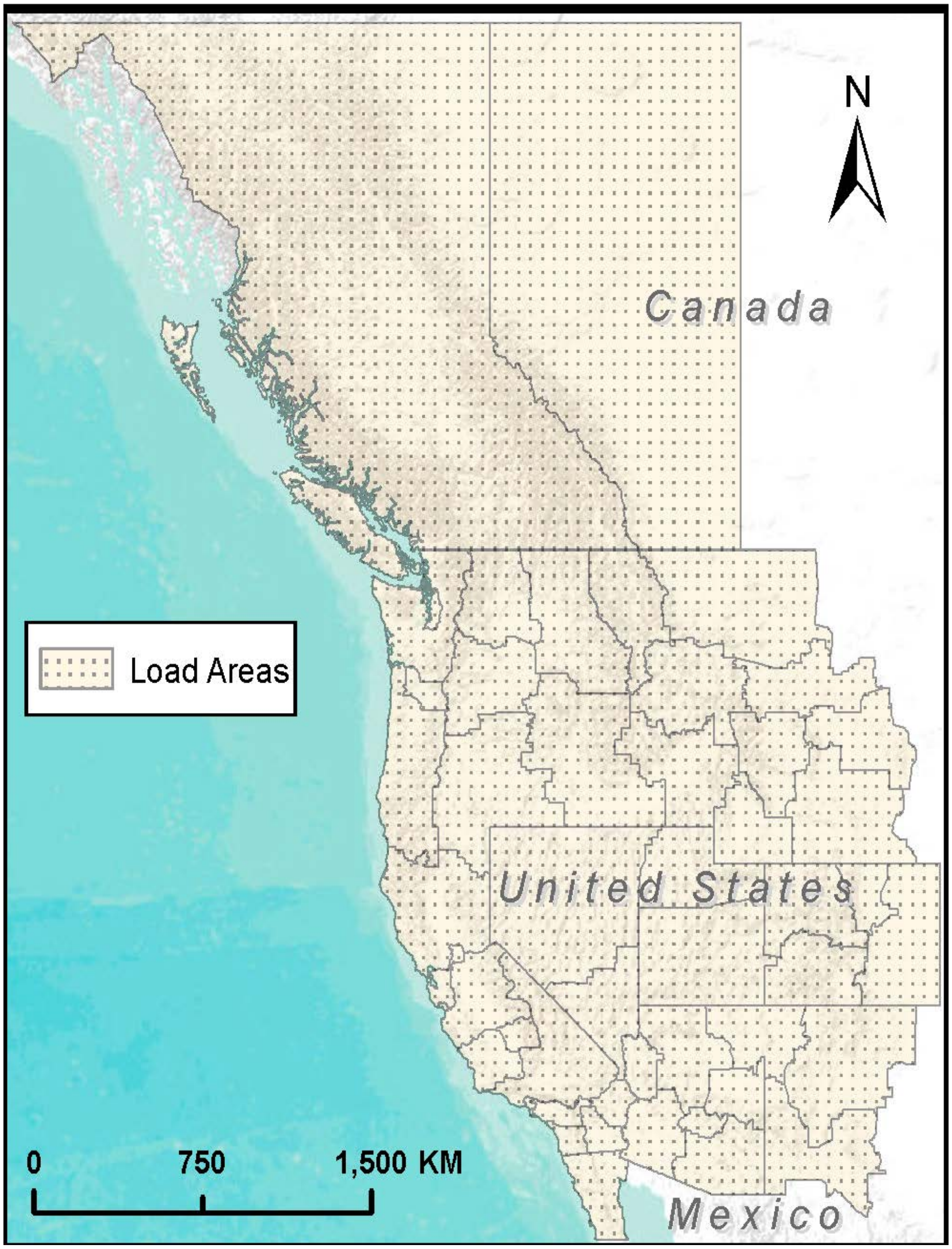

Figure 4. The WECC study region divided into the 50 distinct load areas modeled in SWITCH. (Base map data source: ESRI, USGS, NOAA)

Nelson et al. (2014) describe in detail the data, methods, and assumptions used to identify and characterize existing and new generators, storage technologies, and transmission infrastructure that are simulated and built in the SWITCH model. For the scenarios evaluated, the model can dispatch and/or build the 57 different renewable and conventional generation technologies[27] and types of storage listed in Table 1. The model can also operate existing transmission infrastructure and build new transmission lines between load areas. For each technology, Table 1 lists the fuel consumed, generation or storage classification, and scenarios in which it is included.

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[27] The term "Cogen" next to a technology type in Table 1 indicates that it can be modeled in SWITCH as a cogeneration or combined heat and power facility that jointly generates power and heat.

Table 1. Generation Technologies and types of storage in the SWITCH model

Existing Technologies That Can be Operated	Fuel	Classification	Scenario
Bio Gas Internal Combustion Engine	Bio Gas	Baseload	All
Bio Gas Internal Combustion Engine (Cogen)	Bio Gas	Baseload	All
Bio Gas Steam Turbine	Bio Gas	Baseload	All
Bio Liquid Steam Turbine (Cogen)	Bio Liquid	Baseload	All
Bio Solid Steam Turbine	Bio Solid	Baseload	All
Bio Solid Steam Turbine (Cogen)	Bio Solid	Baseload	All
Coal Steam Turbine	Coal	Flexible Baseload	All
Coal Steam Turbine (Cogen)	Coal	Baseload	All
Combined Cycle Gas Turbine	Gas	Dispatchable	All
Combined Cycle Gas Turbine (Cogen)	Gas	Baseload	All
Distillate Fuel Oil Combustion Turbine	Distillate Fuel Oil	Dispatchable	All
Distillate Fuel Oil Internal Combustion Engine	Distillate Fuel Oil	Dispatchable	All
Gas Combustion Turbine	Gas	Dispatchable	All
Gas Combustion Turbine (Cogen)	Gas	Baseload	All
Gas Internal Combustion Engine	Gas	Dispatchable	All
Gas Internal Combustion Engine (Cogen)	Gas	Baseload	All
Gas Steam Turbine	Gas	Dispatchable	All
Gas Steam Turbine (Cogen)	Gas	Baseload	All
Geothermal	Geothermal	Baseload	All
Hydro (Non-Pumped)	Water	N/A	All
Hydro (Pumped)	Water	Storage	All
Nuclear	Uranium	Baseload	All
Wind (Onshore)	Wind	Intermittent	All
New Technologies That Can be Built	**Fuel**	**Classification**	**Scenario**
Battery Storage	N/A	Storage	All
Bio Gas Internal Combustion Engine	Bio Gas	Baseload	All
Bio Gas Internal Combustion Engine (Cogen)	Bio Gas	Baseload	All
Bio Liquid Steam Turbine (Cogen)	Bio Liquid	Baseload	All
Bio Solid Steam Turbine (Cogen)	Bio Solid	Baseload	All
Biomass Integrated Gasification Combined Cycle	Bio Solid	Baseload	BAU
Coal Integrated Gasification Combined Cycle	Coal	Flexible Baseload	All
Coal Integrated Gasification Combined Cycle with CCS	Coal CCS[2]	Flexible Baseload	All
Coal Steam Turbine	Coal	Flexible Baseload	All
Coal Steam Turbine (Cogen)	Coal	Baseload	All
Coal Steam Turbine (Cogen) with CCS	Coal CCS	Baseload	All
Coal Steam Turbine with CCS	Coal CCS	Flexible Baseload	All
Combined Cycle Gas Turbine	Gas	Dispatchable	All
Combined Cycle Gas Turbine (Cogen)	Gas	Baseload	All

New Technologies That Can be Built (continued)	Fuel	Classification	Scenario
Combined Cycle Gas Turbine (Cogen) with CCS	Gas CCS	Baseload	All
Combined Cycle Gas Turbine with CCS	Gas CCS	Dispatchable	All
Compressed Air Energy Storage	Gas	Dispatchable/ Storage	All
Concentrating Solar Power Trough (with 6h Storage)	Solar	Intermittent	All
Concentrating Solar Power Trough (without Storage)	Solar	Intermittent	All
Gas Combustion Turbine	Gas	Dispatchable	All
Gas Combustion Turbine (Cogen)	Gas	Baseload	All
Gas Combustion Turbine (Cogen) with CCS	Gas CCS	Baseload	All
Gas Combustion Turbine with CCS	Gas CCS	Flexible Baseload	BAU
Gas Internal Combustion Engine (Cogen)	Gas	Baseload	All
Gas Internal Combustion Engine (Cogen) with CCS	Gas CCS	Baseload	All
Gas Steam Turbine (Cogen)	Gas	Baseload	All
Gas Steam Turbine (Cogen) with CCS	Gas CCS	Baseload	All
Geothermal	Geothermal	Baseload	All
Nuclear	Uranium	Baseload	BAU
Photovoltaics (Central)	Solar	Intermittent	All
Photovoltaics (Commercial)	Solar	Intermittent/ Distributed	All
Photovoltaics (Residential)	Solar	Intermittent/ Distributed	All
Wind (Offshore)	Wind	Intermittent	All
Wind (Onshore)	Wind	Intermittent	All

In order to capture interdependences between investment in and operation of the power system, SWITCH simultaneously simulates four levels of temporal resolution: investment periods, months, days, and hours (Nelson et al., 2014). Installed capacity of generation, transmission, and storage infrastructure can only be modified at the start of each of four "investment periods," representing 2016− 2025, 2026− 2035, 2036− 2045, and 2046− 2055 (and referred to here as 2020, 2030, 2040, and 2050, respectively). The existing infrastructure and additional capacity investments in each period constrain the operational possibilities for that period. The periods consist of twelve months of time-synchronized hourly load (electrical demand) and renewable generation profiles based on historical demand, weather, and insolation data. To make optimization computationally feasible, the system is dispatched over two days per month (the peak and median load days) and six hours per day (spaced four hours apart) in each of four periods, for a total of 576 study hours per optimization. All dispatch and investment decisions are optimized concurrently and a post-optimization verification holds the resulting investment decisions fixed while checking that the designed power system can meet demand and operation constraints over a full year of new hourly data. Any shortfalls in capacity identified during verification are compensated by adding more peaking gas combustion turbine capacity to the designed system (Nelson et al., 2013).

B. Future Energy System Scenarios

In this analysis, I evaluate the environmental implications of seven future energy system scenarios: a BAU reference scenario and six distinct decarbonization scenarios. These scenarios were modeled as part of a study for the California Energy Commission that investigated the evolution of the WECC power system in the context of aggressive decarbonization (Nelson et al., 2013, 2014; Wei et al., 2013). The SWITCH model minimizes the cost of generating and delivering electricity to meet projected demand, subject to the various resource availability, reliability, and policy constraints associated with the scenarios. The BAU scenario represents the potential effects of existing carbon reduction policies and is intended to serve as a reference against which the economic and environmental consequences of implementing a more aggressive carbon reduction policy for the WECC power sector can be compared. As such, it should be recognized that the scenarios employed in this analysis are not projections, but minimum-cost strategies to meet decarbonization targets given different economic, resource, and policy assumptions (Nelson et al., 2013, 2014).

All scenarios evaluated in this study assume the parts of the WECC outside of California will decarbonize the electric grid at the same rate as, and in conjunction with, California (Nelson et al., 2014). While this does not reflect the current policy paradigm, Nelson et al. (2014) conclude that it is reasonable to assume there will be future impetus to reduce carbon emissions in the rest of the WECC region, possibly from national or region-wide policies. In 2006, the State of California passed Assembly Bill (AB) 32 requiring GHG emissions be reduced to 1990 levels by 2020. Thus, all scenarios evaluated, including the BAU scenario, assume a reduction in carbon emissions to 1990 levels by 2020. While the BAU scenario assumes no further reduction in carbon emissions thereafter, under the decarbonization scenarios carbon emissions decrease considerably further with a carbon emission cap that declines linearly from 100% of 1990 levels in 2020 to 14% of 1990 levels (40 $MtCO_2\ yr^{-1}$) by 2050. This significant reduction goal is consistent with the state's Senate Bill (SB) 32 which was passed in 2016 and set a target of lowering statewide GHG emissions to 40% of 1990 levels by 2030. It is, however, less aggressive than SB 100, which passed in 2018 and requires the state's electricity to be GHG emission free by 2045.

Electricity demand profiles also differ between the BAU and decarbonization scenarios. WECC-wide electricity demand in the decarbonization scenarios is assumed to increase by 75% by 2050 given population growth as well as electrification of vehicles and heating, tapered by aggressive energy efficiency measures (Wei et al., 2013). Such increased use of electricity for transportation and building climate-control, as well as reductions from energy efficiency, is projected to occur globally by 2050 (Hedberg et al., 2010). On the other had, the BAU scenario assumes electricity demand increases by approximately 83% by 2050 due to population growth and a lack of aggressive efficiency measures, but little electrification of heating or transportation.

While this study focuses on western North America and the scenario parameter settings reflect economic, regulatory, and environmental conditions specific to the study region, the decarbonization scenarios themselves generally reflect energy system transition alternatives receiving widespread international consideration and are relevant to many regions and countries (e.g. see Hedberg et al. 2010; Lincoln 2012). I evaluate a baseline ("Base") decarbonization scenario that reflects currently in place policies and average resource conditions in the study region, as well as average future costs associated with conventional and renewable energy resources. The remaining decarbonization scenarios vary key assumptions from the baseline scenario to reflect specific energy system transition pathways or different resource conditions.

In this analysis, I evaluate the environmental implications of the following six decarbonization scenarios modeled in SWITCH by Nelson et al. (2014):

- **Baseline decarbonization (Base)**: Distinct from BAU, this scenario enforces an 86% reduction in carbon emissions by 2050. It assumes natural gas costs as projected by the EIA's NEMS "Annual Energy Outlook" report base case; average solar PV costs projected by Black & Veatch (2012); a 33% by 2020 RPS for California; three GW of DG built in California; and hydropower generation levels at historical (2004-2011) averages.
- **Low natural gas price (LowNGprice)**: This decarbonization scenario assumes low costs for production of natural gas in the future based on the EIA's NEMS "Annual Energy Outlook" report "high technical recovery of resources" case. Generally this reflects a transition strategy in which natural gas replaces other fossil fuels and plays a significant role in low-carbon electricity production along with carbon capture and storage (CCS)[28] technology.
- **SunShot solar (SunShot)**: This scenario assumes very low installed PV costs are achieved in the near future based on trajectories described in the SunShot Vision Study (United States Department of Energy, 2012). In this case PV costs decline by 2020 to \$1 watt^{-1} for centralized PV installations and \$1.5 watt^{-1} for commercial/residential installations. This scenario represents a carbon reduction pathway that involves widespread deployment of central PV-installations as well as concentrating solar power (CSP) facilities.
- **California distributed generation (CADG)**: This scenario mandates 12GW of small-scale, PV DG (e.g. at the residential and commercial scale) be installed in California by the 2020 investment period. This reflects a strategy that encourages transition towards decentralized renewable energy generation.
- **California 50% renewable portfolio standard (CA50%RPS)**: RPS' require utilities to generate a certain percentage of electricity from renewable resources by a given time period. This scenario increases California's existing 33% by 2020 RPS to 50% by 2030. This scenario is the most specific to the study region, yet is generalizable in that it reflects a transition strategy involving aggressive policies mandating that energy be produced from renewable sources.
- **Limited hydropower (Limited Hydro)**: This scenario represents a situation in which hydropower resources available in the WECC are 50% below their historical (2004-2011) average by 2050. This generally reflects a scenario in which a drought or other consumptive water use reduces a region's hydroelectric renewable output while attempts are being made to decarbonize the power system.

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[28] CCS involves using equipment to capture a majority (e.g. 90%) of carbon emissions from the combustion of fossil fuels and transporting those emissions to a storage facility, usually an underground geologic formation, so they don't enter the atmosphere. CCS technology is currently viable but not widespread due to high implementation costs.

Nelson et al. (2014) provide detailed discussion of the constraints and conditions included in each of the scenarios evaluated in this analysis. Construction of generation plants with CCS is allowed in all scenarios. However, new solid biomass and nuclear plants are excluded from all but the BAU scenario under the assumption that solid biomass will be directed towards fuel for transportation and given California's ban on new nuclear plants. The scenarios enforce all legally binding RPS policies for states in the WECC and RPS targets remain a flat constraint through time after achieving their mandated levels within the required timeframe. Key assumptions specific to the Base and additional decarbonization scenarios are summarized in Table 2.

Table 2. Primary economic, policy, and resource conditions associated with each of the six carbon reduction scenarios.

	Economic Conditions		Policy Conditions		Resource Conditions
Scenario Name	**Natural Gas Costs**	**Solar Costs**	**Renewable Portfolio Standard**	**Distributed Generation (DG)**	**Hydropower Generation**
Base	Average future cost projections	Average future cost projections	33% RPS by 2020 in California	3 GW DG built in California by 2016	Hydropower at 2004-2011 average generation
LowNGprice	Low future cost projections	Base	Base	Base	Base
SunShot	Base	Low future cost projections	Base	Base	Base
CA50%RPS	Base	Base	50% RPS by 2030 in California	Base	Base
CADG	Base	Base	Base	12 GW DG built in California by 2020	Base
Limited Hydro	Base	Base	Base	Base	Hydropower 50% below 2004-2011 average

C. Environmental Impact Factors

Given the investment in, and dispatch of, generation, storage, and transmission from the SWITCH model, I quantify electricity production and newly installed capacity by generator technology and fuel type. I use these quantities, in conjunction with technology specific environmental impact factors, to estimate the environmental effects of each scenario through time and to model the spatial distribution of impacts across load areas in a Geographic Information System (GIS). I derive the impact factors from estimates in the literature that reflect the environmental effects of fuel type-generator technology combinations specific to existing and potential projects modeled in SWITCH. I develop generation-based impact factors for air pollutant emissions (grams (g) $\text{kWh})^{-1}$) and water consumption (L megawatt hour $(\text{MWh})^{-1}$), as well as capacity-based impact factors for land use conversion (ha^2 MW^{-1} for new facilities and ha^2 km^{-1} for new transmission).

Considerable effort in the scientific literature has been devoted to developing metrics that communicate the level of various impacts associated with generating, transmitting, and storing energy from different technologies. Numerous sources have estimated land conversion (e.g. Robeck et al. 1980; Denholm et al. 2009; Fthenakis and Kim 2009; Ong et al. 2013), water use (Bracken et al., 2015; Fthenakis & Kim, 2010; Grubert & Sanders, 2018; Inhaber, 2004;

Macknick, Newmark, et al., 2012; Torcellini, Long, & Judkoff, 2003), or pollutant emissions (e.g. Cai, Wang, Elgowainy, & Han, 2012, 2013) for one or more energy technologies. Other analyses have comparatively evaluated energy technologies across these classes of impacts (Evans, Strezov, & Evans, 2009; L. Gagnon, Bélanger, & Uchiyama, 2002; Hernandez et al., 2014; Jacobson, 2009; Massetti et al., 2017; Onat & Bayar, 2010; Tsoutsos, Frantzeskaki, & Gekas, 2005).

In estimating the impacts of energy technologies, it is important to define consistent system boundaries. Vastly different impact estimates arise from discussions of direct verses life cycle effects. Some argue that consideration should be given to environmental impacts across the entire plant and fuel life cycles including plant construction, operation, decommissioning, fuel production, transportation, refinement, generation, and disposal (L. Gagnon et al., 2002; Inhaber, 2004). However, substantial variability in published life cycle assessments exists as a result of definitional boundary differences, technology characteristics, geographic location, data sources, and methodologies.[29] This can make comparison of life cycle impact estimates for different energy technologies difficult and the estimates themselves less site specific, especially given that the location of some fuel sources are not permanent (Macknick, Newmark, et al., 2012; Sathaye et al., 2011; Weisser, 2007). In this study I focus on the direct, local impacts of energy system expansion and operation within the WECC region under various decarbonization scenarios. Thus, my analysis focuses on the direct air pollution and water consumption effects associated with energy facility operation, as well as the direct land use conversion associated with newly constructed power system infrastructure. I exclude those impacts associated with other stages of the energy life cycle.

I realize that there are numerous exogenous factors that strongly influence local air pollution, water consumption, and land use conversion including for example, vehicle transportation, agriculture, and urban growth, respectively. However, given the scale of the nation's energy system, and as the system becomes increasingly reliant on intermittent, spatially heterogeneous, renewable resources, I believe the local environmental impacts of electricity policy are likely to be of increasing importance to the public and policymakers. Moreover, I recognize that estimates derived from the literature are somewhat generic, and that impacts from specific projects may be greater or smaller according to site conditions, fuel characteristics, mitigation measures, or generator/facility specifications (L. Gagnon et al., 2002). However, given that policy decisions largely precede the availability of individual site- and project-specific information, I argue that analysis based on derived estimates remains highly valuable to decision makers.

C.1. Air Pollution

Major air pollutants from the power sector include sulfur dioxide, nitrogen oxides, particulate matter, and mercury and air toxics. Although regulations promulgated under the 1990 Clean Air Act have helped significantly reduce air pollution from the electricity sector, power plants

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[29] There are two primary life cycle analysis approaches: Process Chain Analysis (PCA) and Input-output (I/O). PCA divides a process into individual flows of materials (and other associated processes) and quantifies their impact from the bottom up, while I/O is a top-down approach that divides the entire economy into distinct sectors and estimates impacts based on economic input/output flows between sectors (Pacca & Horvath, 2002; Weisser, 2007). Hybrids of these methods also exist.

remain the largest source of sulfur dioxide emissions in the United States (Massetti et al., 2017). In 2014, 64% of the nation's sulfur dioxide emissions, 14% of NO_X emissions, 1.4% of PM_{10} emissions, and 3.4% of $PM_{2.5}$ emissions originated from electricity generation, making it one of the dominant industrial sources of such emissions in the United States (Massetti et al., 2017).

In this analysis, I focus on emissions of three "criteria air pollutants" regulated under the EPA's national ambient air quality standards program: SO_X, NO_X, and PM (10 and 2.5 micron). Of the pollutants associated with electricity generation, these three have some of the most significant impacts on human health (World Health Organization, 2006) and are known to reduce agricultural and timber productivity, deteriorate materials, reduce visibility, and harm ecosystems (Massetti et al., 2017). Together SO_X and NO_X are the major cause of acid rain. There is also extensive literature linking these pollutants, in particular PM_{10} and $PM_{2.5}$, to pulmonary and cardiovascular health effects (e.g. see Brunekreef and Holgate 2002; Pope and Dockery 2006). Primary particulate matter and secondary aerosols produced from chemical reactions with NO_x, and SO_x can additionally act as short-lived climate forcing agents that increase climate change effects (Bond et al., 2013; Carmichael, Kulkarni, Chen, Ramanathan, & Spak, 2013).

The emission of air pollutants from electricity generators varies based on factors such as the fuel source, combustion technology, generating unit thermal efficiency, and pollution controls. A majority of electricity-related emissions of SO_X, NO_X, and PM in the United States come from the combustion of fossil fuels (Massetti et al., 2017; U.S. EPA, 2013). In general, fossil fuel electrical generators emit higher levels of NO_x, SO_x, and PM when compared with renewable energy technologies given the fact that fossil generators rely on fuel combustion to produce electricity. Low-carbon technologies such as solar, wind, hydroelectric, geothermal, and nuclear generators are largely considered in the literature to emit no NO_x, SO_x, or PM during operation. Moreover, I found no information in the literature suggesting that energy storage or transmission technologies emit these pollutants during their operation. However, biomass is considered a carbon neutral fuel that emits these pollutants when combusted—although considerably less than fossil fuels (Dayton, 2002; Massetti et al., 2017). Similarly, while CCS technologies can eliminate substantial amounts of carbon emissions from associated fossil fuel plants, they can effectively increase emissions of co-pollutants like NO_X through supplementary power generation needed to offset increased parasitic plant load due to their operation. Rubin, Chen, & Rao (2007) found that CCS technologies remove additional sulfur but little to no nitrogen when used to retrofit pulverized coal and Integrated Gasification Combined Cycle (IGCC) generators. Jacobson (2009), on the other hand, quotes studies finding SO_x emissions to have increased 17.9% with the addition of CCS to an IGCC plant but decreased by 99.7% with the addition of CCS to a pulverized coal plant due to differences in the CCS technologies deployed.

Air Pollutant Emission Factors

This assessment incorporates, with some modification, NO_x, SO_x, PM_{10}, and $PM_{2.5}$ emission factors (EFs) from Argonne National Laboratory's GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model. The GREET factors are calculated from individual plant-level emissions data in the EIA's 2010 Emissions & Generation Resource Integrated Database (eGRID) (Cai et al., 2012). Cai et al. (2012) provide national EFs, state EFs, and in many cases EFs specific to NERC sub-regions (e.g. the WECC region). The national EFs are averages based on fuel type-subtype-generator technology combinations and the state and NERC region EFs are averages based on fuel type-generator technology combinations in a given state or region. Plant-level emissions have been found to correlate among generator and fuel characteristics, so emission factors are likely to be specific to regions (within which fuels have similar chemical contents), fuel types, and technologies (Complainville & Martins, 1994). Given the focus of this analysis on generators throughout a single NERC region (the WECC), I crosswalk the WECC-specific EFs derived by Cai et al. (2012) to generator technology-fuel type combinations modeled in SWITCH wherever possible, and use national values derived by Cai et al. (2012) otherwise.[30]

Table 3 includes the EFs I derive for this analysis. I make a number of assumptions in developing these EFs. I assume solar, wind, geothermal, hydropower, and nuclear generators, as well as storage technologies, do not to emit NO_X, SO_X, or PM in the operational phase. I also assume that existing and newly built generators of the same type have the same EFs and that cogeneration facilities have equivalent emissions to non-cogenerating facilities of the same type. It should be noted that the simplifying assumption that existing and newly built generators of the same type have equal pollutant EFs is not very realistic. Massetti et al. (2017) describe trends and projections for emissions of NO_X and SO_2 from electricity generation between 1990 and 2040 and find that these emissions sharply decline by 2016 in compliance with the EPA's Mercury and Air Toxics Standards regulation, which establishes pollutant emissions limits for new and existing coal- and oil-fired electricity generating units. After 2016, they project emissions will continue to decline at about 1.9% (SO_2) and 1.7% (NO_X) per year until 2040. Thus, the emissions projections in this case should be considered very conservative.

I further assume that the addition of CCS equipment to a generator increases its NO_X emissions due to the parasitic consumption of energy required to operate the CCS infrastructure. Thus, I derate (increase) the GREET NO_X EFs for plants with CCS infrastructure. Based on results reported by Rubin et al. (2007), I increase NO_X emission rates for coal or biosolid steam turbine facilities with CCS by 31%; those for gas combustion turbine, combined cycle, steam turbine, or internal combustion engine facilities with CCS by 17%; and those for coal IGCC facilities with CCS by 16%. Conversely, I assume the SO_X and PM emissions of generators with CCS remain the same as a plant without CCS capabilities given disagreement in the literature on weather CCS infrastructure increases or decreases emission rates of these pollutants (e.g Rubin et al., 2007 vs. Jacobson, 2009).

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[30] Cai et al. (2012) do not specific Coal IGCC EFs for the WECC region specifically so I use national estimates instead. The national estimates include four different sets of EFs for Coal IGCC plants and I adopt the values from the National Energy Technology Laboratory (NETL). Moreover, $PM_{2.5}$ EFs for coal IGCC facilities were not specified in Cai et al. (2012). Thus, I assume no $PM_{2.5}$ emissions from SWITCH coal IGCC facilities in this analysis. Similarly, Cai et al. (2012) do not distinguish biogas or bio liquid fuel subtypes for the WECC region. I use Cai et al.'s (2012) national EF estimates corresponding to landfill gas for SWITCH biogas steam turbine and biogas internal combustion engine facilities, and those corresponding to "other biomass liquid" for SWITCH bio liquid steam turbine facilities.

Table 3. SO_X, NO_X, PM_{10} and $PM_{2.5}$ Emission Factors (all EFs reported in g kWh^{-1})

Existing Technologies	**NO_X**	**SO_X**	**PM_{10}**	**$PM_{2.5}$**
Bio Gas Internal Combustion Engine	2.4282	0.0025	0.5721	0.5721
Bio Gas Internal Combustion Engine (Cogen)	2.4282	0.0025	0.5721	0.5721
Bio Gas Steam Turbine	2.0568	0.0002	0.0943	0.0943
Bio Liquid Steam Turbine (Cogen)	6.632	0.0539	1.8466	1.3078
Bio Solid Steam Turbine	2.1615	3.1468	2.7048	2.4202
Bio Solid Steam Turbine (Cogen)	2.1615	3.1468	2.7048	2.4202
Coal Steam Turbine	1.8544	1.3664	0.4074	0.1542
Coal Steam Turbine (Cogen)	1.8544	1.3664	0.4074	0.1542
Combined Cycle Gas Turbine	0.0722	0.0023	0.001	0.001
Combined Cycle Gas Turbine (Cogen)	0.0722	0.0023	0.001	0.001
Distillate Fuel Oil Combustion Turbine	1.6736	0.3139	0.3823	0.0918
Distillate Fuel Oil Internal Combustion Engine	7.1531	1.0254	0.2876	0.0715
Gas Combustion Turbine	0.3491	0.0065	0.0436	0.0463
Gas Combustion Turbine (Cogen)	0.3491	0.0065	0.0436	0.0463
Gas Internal Combustion Engine	3.7693	0.0186	0.4558	0.4558
Gas Internal Combustion Engine (Cogen)	3.7693	0.0186	0.4558	0.4558
Gas Steam Turbine	0.3119	0.0079	0.0385	0.0385
Gas Steam Turbine (Cogen)	0.3119	0.0079	0.0385	0.0385
Geothermal	0	0	0	0
Hydro (Non-Pumped)	0	0	0	0
Hydro (Pumped)	0	0	0	0
Nuclear	0	0	0	0
Wind (Onshore)	0	0	0	0
New Technologies That Can be Built	**NO_X**	**SO_X**	**PM_{10}**	**$PM_{2.5}$**
Battery Storage	0	0	0	0
Bio Gas Steam Turbine	2.0568	0.0002	0.0943	0.0943
Bio Gas Internal Combustion Engine (Cogen)	2.4282	0.0025	0.5721	0.5721
Bio Liquid Steam Turbine (Cogen)	6.632	0.0539	1.8466	1.3078
Bio Solid Steam Turbine (Cogen)	2.1615	3.1468	2.7048	2.4202
Biomass Integrated Gasification Combined Cycle	0.078	0.322	0.024	0.012
Coal Integrated Gasification Combined Cycle	0.215	0.0044	0.0258	0
Coal Integrated Gasification Combined Cycle with CCS	0.2494	0.0044	0.0258	0
Coal Steam Turbine	1.8544	1.3664	0.4074	0.1542
Coal Steam Turbine (Cogen)	1.8544	1.3664	0.4074	0.1542
Coal Steam Turbine (Cogen) with CCS	2.4293	1.3664	0.4074	0.1542
Coal Steam Turbine with CCS	2.4293	1.3664	0.4074	0.1542
Combined Cycle Gas Turbine	0.0722	0.0023	0.001	0.001
Combined Cycle Gas Turbine (Cogen)	0.0722	0.0023	0.001	0.001
Combined Cycle Gas Turbine (Cogen) with CCS	0.0845	0.0023	0.001	0.001

New Technologies That Can be Built (Continued)	**NO_X**	**SO_X**	**PM_{10}**	**$PM_{2.5}$**
Combined Cycle Gas Turbine with CCS	0.0845	0.0023	0.001	0.001
Compressed Air Energy Storage	0	0	0	0
Concentrating Solar Power Trough (with 6h Storage)	0	0	0	0
Concentrating Solar Power Trough (without Storage)	0	0	0	0
Gas Combustion Turbine	0.3491	0.0065	0.0436	0.0463
Gas Combustion Turbine (Cogen)	0.3491	0.0065	0.0436	0.0463
Gas Combustion Turbine (Cogen) with CCS	0.4084	0.0065	0.0436	0.0463
Gas Combustion Turbine with CCS	0.4084	0.0065	0.0436	0.0463
Gas Internal Combustion Engine (Cogen)	3.7693	0.0186	0.4558	0.4558
Gas Internal Combustion Engine (Cogen) with CCS	4.4101	0.0186	0.4558	0.4558
Gas Steam Turbine (Cogen)	0.3119	0.0079	0.0385	0.0385
Gas Steam Turbine (Cogen) with CCS	0.3649	0.0079	0.0385	0.0385
Geothermal	0	0	0	0
Nuclear	0	0	0	0
Photovoltaics (Central)	0	0	0	0
Photovoltaics (Commercial)	0	0	0	0
Photovoltaics (Residential)	0	0	0	0
Wind (Offshore)	0	0	0	0
Wind (Onshore)	0	0	0	0

C.2 Water Consumption

The electrical power sector in the United States uses far more water than any other sector, suggesting a critical need to understand the impacts of energy production on water resources, especially in the face of potential climate change-related variations in water availability, extended drought, and population growth pressure on water resources (Baker et al., 2014; Grubert & Sanders, 2018; Inhaber, 2004; Lee, Han, Elgowainy, & Wang, 2018; Macknick, Newmark, et al., 2012; Mulder, Hagens, & Fisher, 2010). Water consumption is particularly important in arid climates including the western United States where the high consumption and evaporation rates associated with some forms of energy generation can become limiting factors (Evans et al., 2009), and where recent historic droughts have drawn attention to water provisioning for energy-related uses (Grubert & Sanders, 2018). In this regard, the Western Governor's Association has recognized that energy development and electricity generation may create new water demands and has called for increased coordination across the energy-water nexus (Bracken et al., 2015).

Water use associated with energy production at the power plant level is often divided into two categories: water withdrawal (water that is taken, then returned to circulation) and water consumption (water permanently removed from further use). Some argue that water consumption is an accurate indicator of impact since it is water lost (e.g. Evans et al. 2009). Others suggest withdrawal can impact water resources just as much by increasing temperature or introducing contaminants, and thus imply that both withdrawal and consumption should be considered in impact measures (e.g. Inhaber 2004; Tidwell et al. 2013). In this analysis I focus on consumption of water as the primary environmental impact associated with operation of the power system.

Estimates in the literature suggest hydroelectric and thermal plants using various fuels consume the most water per unit energy while solar PV and wind plants consume the least. Hydroelectric plants withhold water behind dams and cause consumption through evaporation—the magnitude of which varies greatly depending on reservoir size and locational conditions[31] (Evans et al., 2009; Inhaber, 2004; Lee et al., 2018; Macknick, Newmark, et al., 2012; Torcellini et al., 2003). Other power plants consume water during operation for cleaning, cooling, and other process related needs, but the level of consumption is most strongly correlated with the type of cooling system associated with a given generator (Averyt et al., 2011; Baker et al., 2014; Macknick, Newmark, et al., 2012; Torcellini et al., 2003). In general, various sources in the literature contained a range of water consumption estimates associated with a single generator technology but these estimates fell within the same order of magnitude. Differences in water consumption estimates were attributed to issues such as distinguishing between water withdrawal and consumption, inconsistent system boundary definitions, or geographically different physical operational environments (Evans et al., 2009; Grubert & Sanders, 2018; Inhaber, 2004; Jacobson, 2009; Lee et al., 2018; Macknick, Newmark, et al., 2012; Onat & Bayar, 2010)

Thermoelectric plants can be powered by coal, oil, natural gas, nuclear, biomass, or solar resources, and they primarily use water for condenser and reactor cooling. There are two types of thermal cooling technologies: wet cooling, which requires water, and dry cooling, which does not. Wet cooling technologies are by far the most common, and can be further classified as either once-through systems or closed cycle systems with either a cooling pond or tower (Baker et al., 2014; Torcellini et al., 2003). Baker et al. (2014) and Torcellini et al. (2003) provide good overviews of the different cooling system types and mechanisms.

While this analysis focuses on water consumption, it should be noted that there are substantial tradeoffs in amounts of water consumption and withdrawal between different cooling systems (Inhaber, 2004). For example, J. Macknick, Sattler, et al. (2012) find that once-through cooling systems withdraw 10-100 times more water than closed cycle cooling tower systems, yet cooling tower technologies consume twice as much water as one-through technologies. Similarly, Baker et al. (2014) find that a shift to closed cycle technology across the country would lead to a decrease in withdrawals but an increase in consumption.

Low-carbon energy technologies can vary dramatically in consumptive water intensity (Grubert & Sanders, 2018). Non-thermal, low-carbon generation sources such as wind and PV, along with storage technologies and transmission infrastructure, consume very little, if any, water during operation (Evans et al., 2009; Jacobson, 2009; Onat & Bayar, 2010). However, thermal renewable generators such as CSP facilities can consume substantial amounts depending on the type of cooling system employed (Bracken et al., 2015). Grubert and Sanders (2018) argue that geothermal, hydropower, and biomass electricity generation can require an order of magnitude more water consumption than natural gas fired electricity. Facilities that employ CCS for carbon emissions reduction also have higher water consumption per unit energy generated than facilities

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[31] Jacobson (2009) suggests that given the multipurpose nature of hydroelectric reservoirs, not all withdrawal and consumption from these features should be attributed to electricity generation, which can lead to a range of estimates as well.

without such technology due to extra water use for the scrubbers that remove CO_2 (Chandel et al., 2011; Macknick, Newmark, et al., 2012).

Water Consumption Factors

For this analysis, I calculate water consumption factors (CFs) primarily using median water consumption values (CV_{H2O}) reported in a national renewable energy laboratory (NREL) meta-analysis of published water consumption estimates associated with various generator technology-cooling system combinations (J. Macknick et al., 2011).[32] It should be noted that while these published estimates are reported without respect to geographic location, the location of a generator, and its corresponding climatic conditions, are likely to affect its efficiency and water use rate. Additionally, I derive CFs for existing and newly built technologies in SWITCH using slightly different methods.

The SWITCH model technology specifications do not identify the cooling system type of existing generators. Thus, to derive CFs for existing generators, I first calculate the total installed capacity of a generator technology in WECC states in 2008, then the portion of that capacity (capacity weighted percent; $\%_{CAP}$) associated with each of four primary cooling system types (tower, once-through, pond, dry) using data from the Union of Concerned Scientists' EW3 Energy-Water Database (Union of Concerned Scientists, 2012). The calculated $\%_{CAP}$ for each generator type is listed in Table 4. I then derive a single, capacity weighed-average water CF for each existing generator type in switch as the summed products of its cooling-system $\%_{CAP}$ and CV_{H2O} values. For example, Equation 1 is used to calculate the CF for an existing gas combustion turbine (CT):

Equation 1.

$$\begin{aligned} CF_{\text{Gas(CT)}} = {} & ([\%_{CAP} \text{ gas CT tower}] \text{x} [CV_{H2O} \text{ gas CT tower}]) \\ & + ([\%_{CAP} \text{ gas CT once-through}] \text{x} [CV_{H2O} \text{ gas CT tower}]) \\ & + ([\%_{CAP} \text{ gas CT pond}] \text{x} [CV_{H2O} \text{ gas CT pond}]) \\ & + ([\%_{CAP} \text{ gas CT dry}] \text{x} [CV_{H2O} \text{ gas CT dry}]) \end{aligned}$$

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[32] For certain generator-fuel-cooling system combinations in SWITCH, there is no directly corresponding CV_{H2O} from J. Macknick et al. (2011). In these cases I use consumption values from other sources or use J. Macknick et al. (2011) values from other generator-cooling system combinations with a similar fuel type. For gas-fired steam plants with cooling ponds I use the J. Macknick et al. (2011) CV_{H2O} for coal-fired steam plants with cooling ponds. For natural gas combustion turbines and internal combustion engine generators I assign CV_{H2O} values based on data in an unpublished report for the California Energy Commission by Navigant Consulting, Inc. (2007). I assume existing oil combustion turbine and both oil and biogas internal combustion engine plants have similar consumption characteristics to natural gas combustion turbine and internal combustion engine plants and use the same J. Macknick et al. (2011) CV_{H2O} used for their natural gas-fueled counterparts. For coal steam turbines with dry cooling, I use J. Macknick et al. (2011) CV_{H2O} for natural gas steam turbines with dry cooling. Finally, for both existing bio liquid and bio solid generator types I use "biopower, dry (biogas)" and "biopower, tower (steam)" CV_{H2O} values from J. Macknick et al. (2011), but for existing biogas steam turbine plants in SWITCH, I use the "biopower, dry (biogas)" and "biopower, tower (biogas)" CV_{H2O} values from J. Macknick et al. (2011).

Table 4. Capacity weighted percentages of existing generator technologies modeled in SWITCH

Fuel-Generator Technology (Cooling Type) Combination	WECC States Installed Capacity (MW)	Percent Capacity of Combination ($\%_{CAP}$)
Coal-steam turbine (dry cooling)	646.7	2%
Coal-steam turbine (once through)	808.5	2%
Coal-steam turbine (pond)	3758.4	12%
Coal-steam turbine (cooling tower)	27215.6	84%
Natural gas-steam turbine (once through)	14344.7	74%
Natural gas-steam turbine (pond)	474.8	2%
Natural gas-steam turbine (cooling tower)	4477.5	23%
Natural gas-combined cycle (dry cooling)	7582.2	16%
Natural gas-combined cycle (once through)	2467.6	5%
Natural gas-combined cycle (pond)	1321.9	3%
Natural gas-combined cycle (cooling towers)	36868.5	76%
Natural gas-combustion turbine (no cooling)	16522.7	100%
Oil-combustion turbine (no cooling)	964.2	100%
Nuclear-steam turbine (once through)	4577	46%
Nuclear-steam turbine (cooling tower)	5409.3	54%
Hydro-hydro (no cooling)	48814.8	100%
Hydro-pumped storage (no cooling)	2791	100%
Biopower, biogas-steam turbine (dry cooling)	186.5	19%
Biopower, biogas-steam turbine (cooling tower)	804.2	81%
Photovoltaics-photovoltaics (no cooling)	53.6	100%
Geothermal-binary (cooling tower)	369.8	12%
Geothermal-dry steam (cooling tower)	1559.8	51%
Geothermal-EGS (cooling tower)	1108.8	36%
Wind-wind (no cooling)	7217.2	100%

For new generators constructed in the SWITCH model during future investment periods, I assume the cooling system is as specified for the generator type in Black & Veatch (2012b) given that the operational characteristics and capital and operational costs for new generator technologies in the SWITCH model are derived from this text. As with existing generators, I apply corresponding CV_{H2O} reported by J. Macknick et al. (2011) for that generator technology-cooling system combination. If a cooling system is not specified for a given generator technology in Black & Veatch (2012b), I make the simplifying assumption that the generator type will have a tower cooling system based on the trend away from once-through cooling mechanisms for electrical generators in the western United States (Baker et al., 2014). One exception is for geothermal generators which, according to the California Energy Commission (2013), will be binary, hydrothermal plants with dry cooling. I also assume that generators with CCS infrastructure have higher consumption than the same generator type without CCS infrastructure because CCS technologies require high amounts of water for operation.[33] On the other hand, new commercial and residential solar PV, onshore and offshore wind, and storage technologies are assumed not to consume any water in the operational phase. New hydropower is not currently built in the version of the SWITCH model used in this analysis. Table 5 includes the water CFs derived for existing and newly constructed generators modeled in SWITCH.

Table 5. Water consumption factors for new and existing technologies in SWITCH

Existing Technologies	**Water CF (L MWh^{-1})**
Bio Gas Internal Combustion Engine	3.79
Bio Gas Internal Combustion Engine (Cogen)	3.79
Bio Gas Steam Turbine	745.65
Bio Liquid Steam Turbine (Cogen)	1722.18
Bio Solid Steam Turbine	1722.18
Bio Solid Steam Turbine (Cogen)	1722.18
Coal Steam Turbine	2445.11
Coal Steam Turbine (Cogen)	2445.11
Combined Cycle Gas Turbine	639.67
Combined Cycle Gas Turbine (Cogen)	639.67
Distillate Fuel Oil Combustion Turbine	302.80
Distillate Fuel Oil Internal Combustion Engine	3.79
Gas Combustion Turbine	302.80
Gas Combustion Turbine (Cogen)	302.80
Gas Internal Combustion Engine	3.79
Gas Internal Combustion Engine (Cogen)	3.79
Gas Steam Turbine	1449.66
Gas Steam Turbine (Cogen)	1449.66
Geothermal	832.70
Hydro (Non-Pumped)	16998.44
Hydro (Pumped)	16998.44
Nuclear	1843.30
Wind (Onshore)	0.00
New Technologies That Can be Built	**Water CF (L MWh^{-1})**
Battery Storage	0.00
Bio Gas Steam Turbine	302.80
Bio Gas Internal Combustion Engine (Cogen)	3.79

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[33] I rely on J. Macknick, Newmark, et al. (2012) CV_{H2O} values that take into account CCS technology as CFs for newly built coal steam turbines and integrated gasification combined cycle plants with CCS. Water CFs for gas steam turbine plants with CCS were not identified directly in the literature I reviewed, so I assume a 58% increase in water consumption above the same plant without CCS. This is equivalent to the percent increase in water consumption for a coal steam turbine with CCS as cited by the National Energy Technology Laboratory (2007) in a report on performance baselines for fossil fuel power plants. For new gas combustion turbines or internal combustion engine plants with CCS, I assume the addition of CCS increases plant water consumption by 91% which is equivalent to the percent increase for a gas combined cycle plant with CCS cited by the same report.

New Technologies That Can be Built (Continued)	Water CF (L MWh^{-1})
Bio Liquid Steam Turbine (Cogen)	2093.11
Bio Solid Steam Turbine (Cogen)	2093.11
Biomass Integrated Gasification Combined Cycle	1438.30
Coal Integrated Gasification Combined Cycle	1438.30
Coal Integrated Gasification Combined Cycle with CCS	2077.97
Coal Steam Turbine	1866.01
Coal Steam Turbine (Cogen)	1866.01
Coal Steam Turbine (Cogen) with CCS	3202.11
Coal Steam Turbine with CCS	3202.11
Combined Cycle Gas Turbine	775.93
Combined Cycle Gas Turbine (Cogen)	775.93
Combined Cycle Gas Turbine (Cogen) with CCS	1487.51
Combined Cycle Gas Turbine with CCS	1487.51
Compressed Air Energy Storage	0.00
Concentrating Solar Power Trough (with 6h Storage)	295.23
Concentrating Solar Power Trough (without Storage)	295.23
Gas Combustion Turbine	302.80
Gas Combustion Turbine (Cogen)	302.80
Gas Combustion Turbine (Cogen) with CCS	579.11
Gas Combustion Turbine with CCS	579.11
Gas Internal Combustion Engine (Cogen)	3.79
Gas Internal Combustion Engine (Cogen) with CCS	7.57
Gas Steam Turbine (Cogen)	3126.41
Gas Steam Turbine (Cogen) with CCS	4939.43
Geothermal	1021.95
Nuclear	2543.52
Photovoltaics (Central)	3.79
Photovoltaics (Commercial)	0.00
Photovoltaics (Residential)	0.00
Wind (Offshore)	0.00
Wind (Onshore)	0.00

C.3. Land Use Conversion

Energy technologies have direct impacts on land cover caused by the removal of land from its previous usage to construct and operate associated infrastructure (Fthenakis & Kim, 2009; Kiesecker & Naugle, 2017; McDonald et al., 2009; Robeck et al., 1980). In addition to generation and storage technologies, this includes transmission infrastructure which often necessitates the establishment of power line corridors with maintained rights-of-way (ROW) that can have direct consequences for land cover[34] (Dale et al., 2011). The siting of energy generation, storage, and transmission infrastructures transforms the existing landscape, removing soil and ground vegetation and increasing the potential for erosion and sedimentation loading to waterways (Massetti et al., 2017). Moreover, land use for energy development can cause significant habitat loss and fragmentation resulting in impacts to biodiversity and ecosystem services (Bare et al., 2009; McDonald et al., 2009; Trainor et al., 2016). Kiesecker et al. (2017) note that species and ecological systems need large, intact natural habitats that they can migrate through to preserve their potential to adapt to a changing climate, and the irony of the push to develop renewable energies to alleviate climate change is that the potential benefit of this mitigation to biodiversity will only be realized if such renewable energy development can minimize impacts to critical, intact habitats.

Energy technologies vary in the spatial extent they require to produce, transmit, and/or store a fixed amount of energy (i.e. the inverse of power density). This measure is often referred to as their land use factor or land use energy intensity[35] (LUEI; R. M. Horner & Clark, 2013; Massetti et al., 2017; McDonald et al., 2009). Like Massetti et al. (2017), I find there is limited published literature comparing land use factors and impacts across electricity generating technologies. Among published land use estimates for individual energy technologies, it can be difficult to draw comparisons. This is because studies vary in whether land use estimates refer to all land enclosed by the project site boundary (which is typically fenced/protected) or to only the land directly occupied by physical infrastructure within the site boundary (R. M. Horner & Clark, 2013; Ong et al., 2013) as well as whether they evaluate only direct land use or life-cycle land use (Massetti et al., 2017). For these same reasons, estimates of LUEI for a single technology can vary widely in the literature (Fthenakis & Kim, 2009; L. Gagnon et al., 2002; R. M. Horner & Clark, 2013). For example, Horner & Clark (2013) found current published studies on land use for solar electricity generation present estimates covering four orders of magnitude while Fthenakis and Kim (2009) suggest that a 1000 MW coal plant in the United States can require between 330 and 1000 acres^2 (133.5 and 404.7 ha^2) depending on plant design and associated facilities. The values in this analysis are intended to reflect the total area enclosed by the boundary of a typical energy generation, storage, or transmission facility during the operational phase, as opposed to only the land occupied by physical infrastructure within that boundary.

Comparatively, low-carbon generation options generally have high LUEI relative to conventional fossil fuel generators, and land conversion is commonly cited as an important potential environmental tradeoff associated with decarbonizing the electricity sector (Denholm & Margolis, 2008; Fthenakis & Kim, 2009; L. Gagnon et al., 2002; Kiesecker & Naugle, 2017; Ong et al., 2013; Trainor et al., 2016). Considering the full facility boundary, hydroelectric facilities followed by wind- and solar-based technologies require more land area per unit energy generated than conventional fossil fuels and nuclear generation, a result concluded by many studies (Denholm & Margolis, 2008; Fthenakis & Kim, 2009; L. Gagnon et al., 2002; Ong et al.,

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[34] Although land use and land cover are often used interchangeably, land use refers to how land is used by humans (e.g. residential vs. agricultural), while land cover refers to the vegetation, structures, or other features on the land.

[35] Massetti et al. (2017) differentiate “Land use factor” as a measure of the generation capacity per land area of a typical power plant facility (e.g., MW/km^2) and “Land use intensity” as the portion of the land area within a power plant facility that is disturbed or directly occupied by the plant’s infrastructure and operations. However, these are often used interchangeably in the broader literature.

2013; U.S. Department of Energy, 2015). However, while wind energy has one of the highest area requirements per unit energy, the literature estimates that only approximately 1-10% of the full facility boundary is actually physically transformed or occupied permanently by turbines and related infrastructure (Massetti et al., 2017; U.S. Department of Energy, 2015). Such land may therefore be characterized by the opportunity for multiple uses (such as housing, agriculture, grazing or others) in the space between turbines (Evans et al., 2009; Fthenakis & Kim, 2009; Jacobson & Delucchi, 2011; U.S. Department of Energy, 2015). Thus, the site boundary based LUEI definition applied in this analysis should be considered very conservative in estimating the land use conversion necessary for wind projects given that other uses may occur between turbines. Among conventional generators fossil fuel technologies have the smallest land use requirements per unit of energy produced. The land requirement of nuclear power plants are higher than that of fossil fuel plants because nuclear plants require a safety exclusion and barrier space (Massetti et al., 2017; Robeck et al., 1980).

Certain forms of storage as well as transmission infrastructures also require land use conversion. The addition of CCS technologies presumably increases the land area required by fossil fuel systems by an amount but I found only one data point generally quantifying a small increase (Massetti et al. (2017) suggest CCS infrastructure requires 10% or less of a facility's area). Battery based storage is likely to require negligible amounts of additional land use conversion according to U.S. Department of Energy and Electric Power Research Institute (1997). Compressed air energy storage (CAES) generally is designed to involve large sub-surface reservoirs for storing compressed air, but can require additional land use conversion for associated above ground operation facilities (Beckwith & Associates, 1983). While high-voltage electric transmission lines are generally mounted on poles or buried underground, they do require land use conversion for transmission ROW, which are often maintained for access and to remove threats to transmission infrastructure (e.g. tall vegetation).

Land Use Conversion Factors

This analysis focuses on new land use conversion necessary for expansion of the power system, including newly constructed transmission infrastructure. I do not calculate the land area occupied by existing electric system infrastructure. As noted, estimates for generator and storage projects are based on the total area enclosed by the project's site boundary, not the area occupied by physical system infrastructure within that boundary.

I assume that residential and commercial PV installations do not require land use conversion because they are generally installed on/over built structures (Massetti et al., 2017). Similarly, I assume offshore wind requires no terrestrial land use conversion. Moreover, I do not include land conversion for hydroelectric facilities given that the version of the SWITCH model used for this analysis does not allow for construction of new hydropower facilities. The land area available for development and associated total potential capacity for individual central PV and CSP projects are input parameters in SWITCH. Thus, I multiply the MW of each project installed in a scenario by its area per MW input factor to calculate the amount of land converted for such facilities in the modeling process. For new transmission infrastructure built in the SWITCH model scenarios, I estimate the land use conversion as the length of new transmission pathway established (in km) times a WECC-specific average ROW area factor of 22.50 acres^2 mile^{-1} (5.65 ha^2 km^{-1}) derived from a Black & Veatch (2012a) survey of industry ROW width assumptions for the WECC by voltage class. Consistent with other studies (e.g. Jacobson et al. 2014), I assume any increases in transmission capacity along existing transmission pathways will be accomplished through enhanced lines without requiring additional ROW. For all other newly built energy technology types in SWITCH, I incorporate from the literature estimates of the land area required per MW installed.

Table 6 contains the land use conversion factors derived from the literature for the technologies modeled in this analysis. I found little data on the direct land requirements for natural gas generators so assume that they require similar levels of land use conversion as oil facilities and adopt a land use value specified for oil plants in an Argonne National Laboratory report on land use and energy (Robeck et al. 1980). I apply the same value for steam turbine, combined cycle, combustion turbine, or internal combustion engine natural gas plants. I employ a land use conversion value for coal plants from Fthenakis and Kim (2009). This conversion value is as specific to the western United States and is lower than the U.S. average they report. I found no specific data on the difference in land area required for production from coal steam turbine verses coal IGCC facilities and thus use the same value for all new coal generator technologies in the SWITCH model. Robeck et al. (1980) provide estimates of land area occupied by nuclear reactor facilities in different regions of the United States in 1975. Regions 8, 9, and 10 correspond to states in the WECC, however region 8 did not have any nuclear plants at that time. Thus, I take the average of the acres/MW reported for nuclear plants in regions 9 and 10 for this analysis. I adopt land use conversion factors for biomass and geothermal facilities from U.S. Department of Energy and Electric Power Research Institute (1997). I assign their biomass gasification plant area estimate for the year 2030 to SWITCH biomass IGCC generators and their biomass combustion plant area estimate for 2030 to biogas, bio liquid, and bio solid steam turbine and biogas internal combustion engine generators modeled in SWITCH.

For new wind projects, the SWITCH model identifies potential locations based on the Western Wind and Solar Integration Study (GE Energy, 2010) which assumes a spacing of five, 3MW Vestas V90 turbines km^{-2} (15 MW km^{-2} or 6.67 ha^2 MW^{-1}). I employ the land use conversion factor from GE Energy (2010) for new wind plants in this analysis for consistency with the SWITCH model assumptions. This spacing is slightly more dense than the high end of the range observed by Denholm, Hand, Jackson, & Ong (2009) who collected data on the total area of 161 wind projects and found them to have a capacity land density of 2-10 MW km^{-2}. Denholm et al. (2009) note, however, that their observed MW km^{-1} density is likely higher than estimates used for optimizing energy extraction because the ideal grid configuration is rarely achieved in practice given terrain variations such as depressions and ridges, which result in more widely spaced turbines. Thus, the GE Energy (2010) estimate I use may further underestimate the area necessary for a wind facility.

While CCS technologies presumably increase the land area required by fossil fuel systems by a small amount, given the limited data quantifying this increase and the fact that this amount of area could fit within the existing facility boundary for associated generators, I make the simplifying assumption that the additional land use conversion is negligible. I also assume additional land use conversion at a facility for battery storage to be negligible. For compressed air energy storage I apply a land use conversion factor from a report by Beckwith & Associates

(1983) that cites a 1000 MW CAES facility proposed in Illinois was expected to require approximately 200 acres^2 of land for surface facilities.

Table 6. Land use conversion factors for new technologies that can be built in the SWITCH model

New Technologies Built	Land Use CF (ha^2 MW^{-1})
Battery Storage	0.00
Bio Gas Steam Turbine	0.90
Bio Gas Internal Combustion Engine (Cogen)	0.90
Bio Liquid Steam Turbine (Cogen)	0.90
Bio Solid Steam Turbine (Cogen)	0.90
Biomass Integrated Gasification Combined Cycle	0.37
Coal Integrated Gasification Combined Cycle	0.13
Coal Integrated Gasification Combined Cycle with CCS	0.13
Coal Steam Turbine	0.13
Coal Steam Turbine (Cogen)	0.13
Coal Steam Turbine (Cogen) with CCS	0.13
Coal Steam Turbine with CCS	0.13
Combined Cycle Gas Turbine	0.03
Combined Cycle Gas Turbine (Cogen)	0.03
Combined Cycle Gas Turbine (Cogen) with CCS	0.03
Combined Cycle Gas Turbine with CCS	0.03
Compressed Air Energy Storage	0.08
Concentrating Solar Power Trough (with 6h Storage)	Calculated from SWITCH Inputs
Concentrating Solar Power Trough (without Storage)	Calculated from SWITCH Inputs
Gas Combustion Turbine	0.03
Gas Combustion Turbine (Cogen)	0.03
Gas Combustion Turbine (Cogen) with CCS	0.03
Gas Combustion Turbine with CCS	0.03
Gas Internal Combustion Engine (Cogen)	0.03
Gas Internal Combustion Engine (Cogen) with CCS	0.03
Gas Steam Turbine (Cogen)	0.03
Gas Steam Turbine (Cogen) with CCS	0.03
Geothermal	2.00
Nuclear	0.53
Photovoltaics (Central)	Calculated from SWITCH Inputs
Photovoltaics (Commercial)	0.00
Photovoltaics (Residential)	0.00
Wind (Offshore)	0.00
Wind (Onshore)	6.67

D. Quantifying Future Environmental Effects

In order to calculate the environmental effects of each scenario through time and across spatial scales, I combine electricity production and installed capacity outputs from the SWITCH model with the environmental impact factors derived for this analysis. In SWITCH, the time steps modeled represent present day (or the 2013-2016 period when the scenarios were modeled in SWITCH), 2020, 2030, 2040, and 2050. For each scenario, I query the SWITCH model output data to obtain the average annual electricity production and total newly installed capacity per time period by fuel type-generator technology combination, both in each load area and across the WECC region as a whole. I multiply these quantities by the fuel type-generator technology specific air pollution, water consumption, and land use conversion impact factors, to estimate the environmental effects of each scenario through time. For scenarios and time periods of interest, I model in GIS the spatial distribution of these effects across load areas. Air pollutant and water consumption calculations are generation-based, multiplying the average annual kWh or MWh produced from a fuel type-generator technology combination in a time period by associated impact factors in g kWh^{-1} and L MWh^{-1}. Land use conversion calculations are capacity-based, multiplying total newly installed fuel type-generator technology capacity or kilometers of transmission ROW in a time period by associated impact factors in ha^2 MW^{-1} for generators and ha^2 km^{-1} for transmission.

III. Results

The results of this analysis show that despite achieving equivalent reductions in carbon emissions (14% of 1990 levels by 2050), the six decarbonization scenarios engender both similarities and differences in environmental implications through time and across the WECC region. The scenarios do show similar broad trends in environmental impacts, with each decarbonization scenario resulting in reduced WECC-wide air pollution and water consumption relative to the BAU reference scenario, but requiring greater land use conversion. However, I find that the magnitude of these benefits and impacts varies across the decarbonization scenarios themselves by as much as 108,000 t of annual air pollution, $145\text{x}10^9$ L of annual water consumption, and 491,500 ha^2 of cumulative land conversion. Additionally, I find large spatial variation in these environmental factors across load areas both within and among the scenarios.

A. WECC Air Pollutant Emissions

Average annual emissions of WECC-wide NO_x, SO_x, PM_{10}, and $PM_{2.5}$ under the six carbon reduction scenarios follow similar general trajectories through time, with the greatest emission variation across scenarios occurring in the 2030 period. Emissions of all four pollutants under the decarbonization scenarios are higher than the BAU emissions in the 2020 period, decline below the BAU emissions in the 2030 period, and continue to decline through to the 2050 period, while the BAU emissions sharply rise (Figure 5a-d). The high pollutant emissions from the carbon reduction scenarios in the 2020 period (relative to BAU) result from additional coal-based emissions to balance intermittent renewable energy additions. The subsequently higher BAU emissions in the 2030-2050 periods stem from higher coal-, coal ccs-, and gas-based emissions possible in this scenario given the lower carbon reduction constraint imposed in BAU (Figure 5a-d). Across all seven scenarios (i.e. BAU and the six decarbonization scenarios), average annual quantities of NO_x emitted are the highest in each period (475-40 kilotonnes [kt]), followed by emissions of SO_x (320-10 kt), PM_{10} (100-13 kt), and $PM_{2.5}$ (50-11 kt).

Among the decarbonization scenarios, those that encourage installation and operation of intermittent renewables (CA50%RPS and SunShot) tend to have the highest average annual non-CO_2 air pollutant emissions in the near future (through the 2030 time period) but decline to the lowest average annual emissions by the mid-century time period. The converse is generally true for the scenarios that result in comparatively more reliance on fossil fuels (LowNGprice and Limited Hydro). In the 2030 time period when emission variation across the scenarios is greatest, average annual NO_x emissions are the highest for the CA50%RPS (149 kt) and SunShot scenarios (144 kt) and the lowest for the LowNGprice (105 kt) and Limited Hydro scenarios (99 kt), with the Base and CADG scenarios having nearly equivalent, intermediate average annual NO_x emissions (132 kt) (Figure 6a). These differences stem largely from variation in coal-based NO_x emissions (Figure 6a). In contrast, by the 2050 time period, annual average NO_x emissions from the SunShot scenario are the lowest (38 kt) and those of the LowNGprice scenario (47 kt) are the highest, due largely to additional emissions from operation of natural gas generators with CCS infrastructure (Gas CCS). The carbon reduction scenarios show the same relative trend for average annual SO_x emissions in the 2030 time period, but in the 2050 time period the SunShot and LowNGprice scenarios have equivalently low average annual SO_x emissions (approximately 11 kt) due to less emissions from operation of coal generators with CCS infrastructure (Coal CCS) than in the other scenarios during this period (Figure 6.b). In the 2030 time period the CA50%RPS scenario has the highest average annual PM_{10} (39 kt) and $PM_{2.5}$ (26 kt) emissions of the decarbonization scenarios, approximately equal those of the BAU scenario (Figure 6c, Figure 6d). The Limited Hydro and LowNGprice scenarios have the lowest average annual PM_{10} emissions (26 and 27 kt, respectively) in the 2030 time period, while the SunShot scenario has the lowest $PM_{2.5}$ emissions (20 kt). These variations in PM emissions are primarily driven by differences in coal- and solid biomass-based generation (Figure 6.c, Figure 6d). By the 2050 time period, average annual PM emissions across all six scenarios are similar, falling within a range of 0.5 kt of one another.

The simulated increase in average annual pollutant emissions for the decarbonization scenarios above the BAU reference scenario in the near term 2020 time period and relatively high levels of emissions for the CA50%RPS and SunShot scenarios in 2030 is generally consistent with other studies which suggest that integration of low carbon renewable generators can increase system wide emissions due to increased dispatch of fossil fuel-based generation to offset renewable resource intermittency (Blumsack & Xu, 2011; Katzenstein & Apt, 2009). However, the subsequent decline in average annual pollutant emissions well below those of BAU after the 2030 time period, along with the fact that the SunShot scenario has the lowest average annual NO_x, SO_x, and $PM_{2.5}$ emissions by the 2050 time period, suggest that aggressive carbon reduction and renewable integration in the electricity sector can result in the lowest average annual air pollutant emissions in the long term.

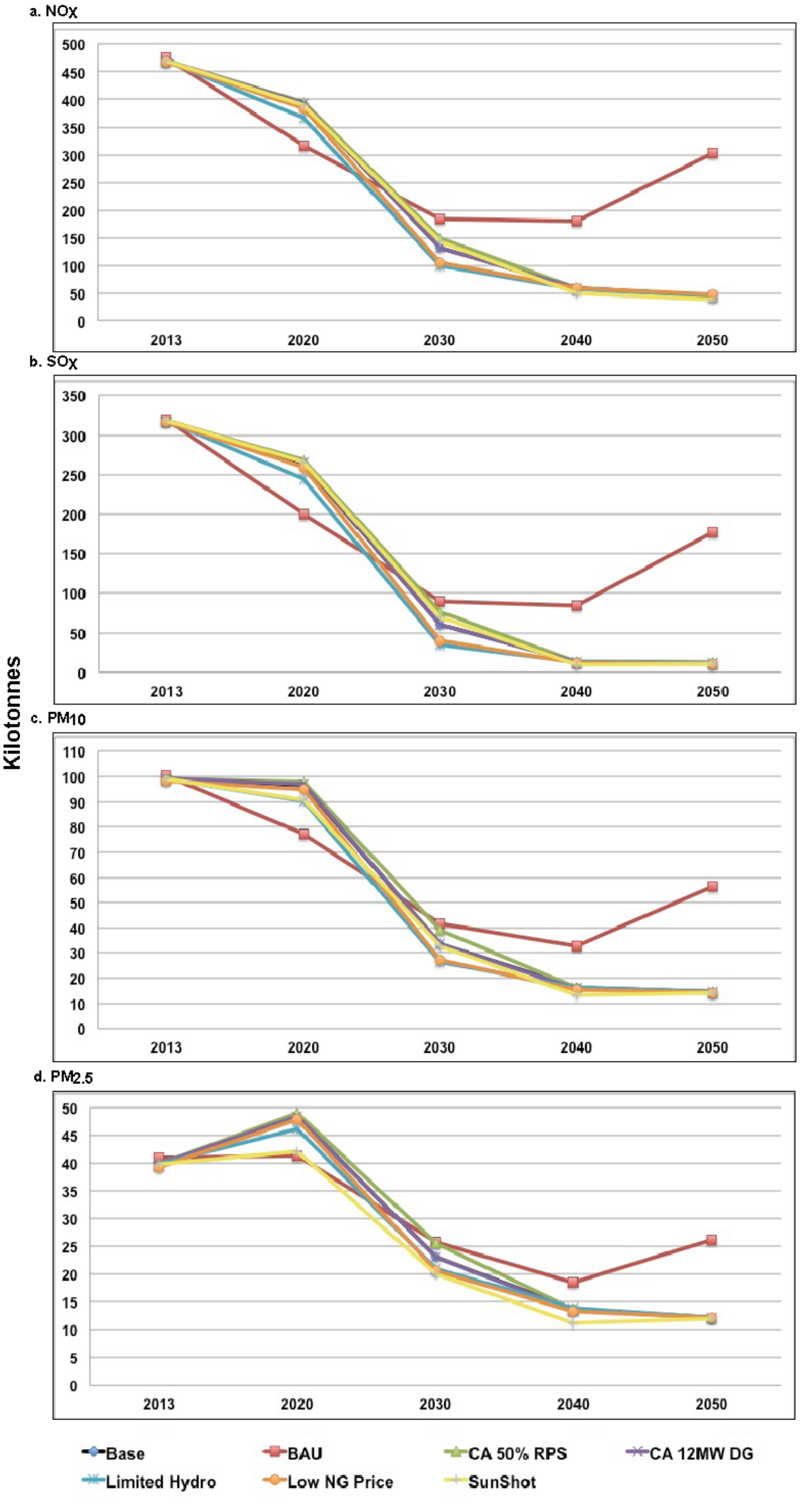

Figure 5. Average annual WECC-wide pollutant emissions in each period across scenarios. Graphs a-d show NOx, SOx, PM10, and PM2.5 levels, respectively.

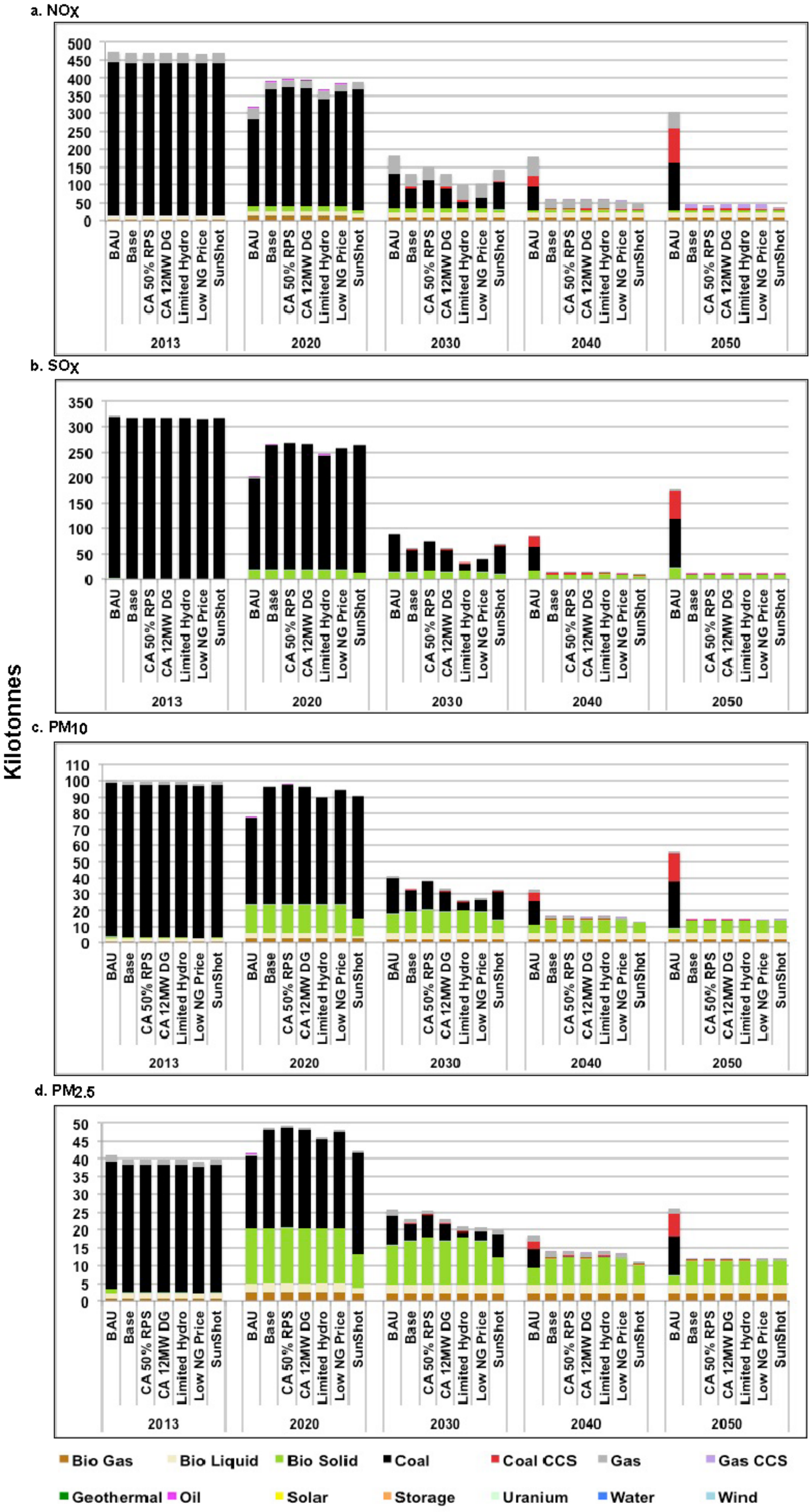

Figure 6. Average annual WECC-wide pollutant emissions in each period across scenarios by fuel source. Graphs a-d show NOx, SOx, PM10, and PM2.5 levels, respectively. Each time period (x-axis) includes columns representing (in order) the BAU, Base, CA50%RPS, CADG, Limited Hydro, LowNGprice, and SunShot scenarios.

Given the high variation in WECC-wide average annual pollutant emissions in the 2030 timeframe, I model in GIS the spatial distribution of load area average annual emission densities (t km^{-2}) in the 2030 time period. The results for the LowNGprice and SunShot scenarios are shown in Figure 7 and , respectively. The size of the representative circle for each load area in these figures captures the combined average annual air pollutant density (the sum of the emissions of NO_x, SO_x, PM_{10}, and $PM_{2.5}$ divided by the size of the load area in km^2), while the colored slices of each circle represent the proportional contribution of NO_x, SO_x, PM_{10}, and $PM_{2.5}$ emissions to the total air pollutant density. The LowNGprice (Figure 7) and SunShot (Figure 8) scenarios have relatively low and high total average annual emissions of the four pollutants in 2030 respectively, and their potential environmental effects are of particular interest because they represent two distinct pathways proposed to achieve carbon emission reductions – expanded use of natural gas as a transition fuel or rapid transition to increased solar energy production.

In both scenarios, the combined average annual emission densities of the four pollutants (i.e. the sizes of the load areas' circles) show a wide range across the study region. Densities for the SunShot scenario (Figure 8) ranged from 77 g to 1.65 t km^{-2} while those in the LowNGprice scenario (Figure 7) ranged from 124 g to 1.84 t km^{-2}. In both scenarios, load areas along the west coast, especially in the southern California region, show large average annual combined emission densities relative to the rest of the WECC. However, these load areas have greater combined emission densities under the SunShot scenario than under the LowNGprice scenario. Investigating the fuel type-generator technology source data, I find that in the SunShot scenario, these load areas tend to have higher levels of average annual emissions associated with coal and biomass based generation in the 2030 time period relative to the LowNGprice scenario. The largest difference in load area average annual combined emission density between the two scenarios in the 2030 period is seen in the eastern Arizona load area (outlined in blue in both figures). This load area experiences a low density of 5.25 kilograms (kg) km^{-2} in the LowNGprice scenario (Figure 7) verses a high density of 1.09 t km^{-2} in the SunShot scenario (Figure 8). Based on the fuel type-generator technology source data for this load area, this difference stems from coal-based generation with high pollutant EFs in the load area under the SunShot scenario verses gas-based generation with comparatively lower pollutant EFs under the LowNGprice scenario.

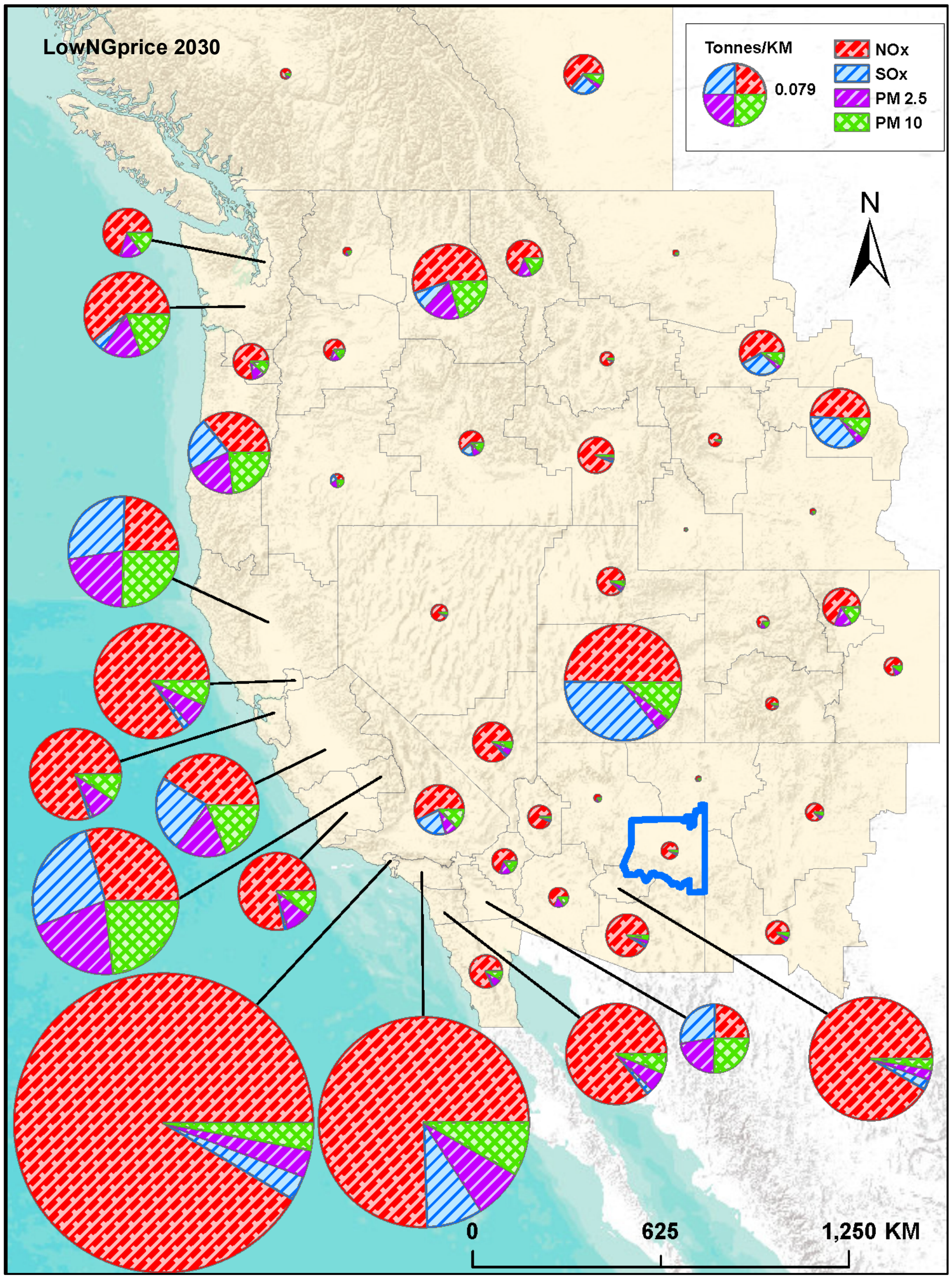

Figure 7. Annual air pollutant emission densities (t km^{-2}) within each load area in the 2030 time period for the LowNGprice scenario. The eastern Arizona load area (blue outline) shows the largest difference in emission densities between this scenario and the SunShot scenario that shown in the next figure. (Base map data source: ESRI, USGS, NOAA)

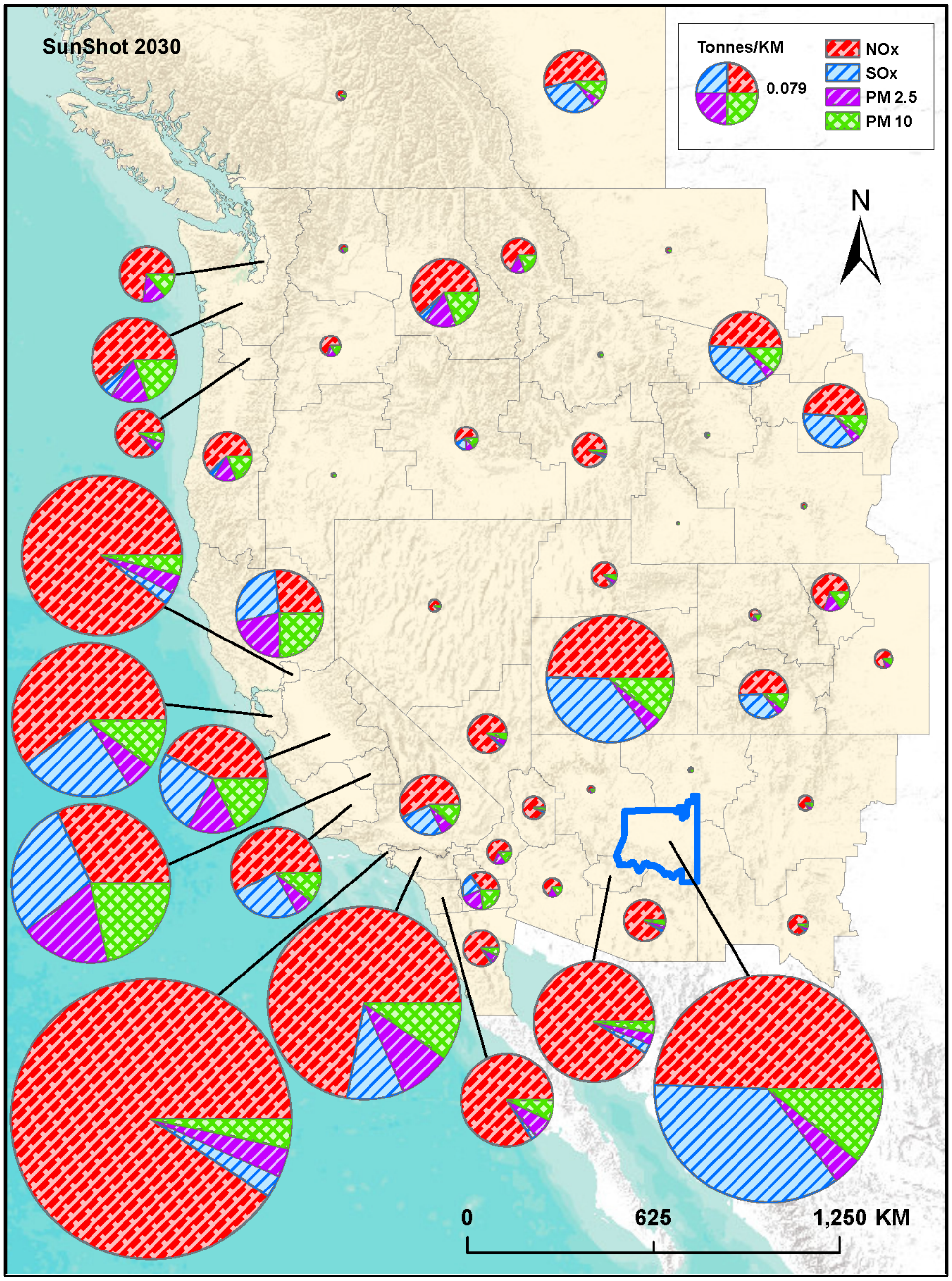

Figure 8. Annual air pollutant emission densities (t km^{-2}) within each load area in the 2030 time period for the SunShot scenario. The eastern Arizona load area (blue outline) shows the largest difference in emission densities between this scenario and the LowNGprice scenario shown in the prior figure. (Base map data source: ESRI, USGS, NOAA)

While the SWITCH model makes investment and dispatch decisions within load areas, pollutant emissions are primarily regulated within air basins that encompass portions of multiple load areas. Given this, I re-aggregate the LowNGprice and SunShot 2030 average annual scenario emissions from load areas to California air basins though area interpolation in GIS in order to characterize the potential average annual criteria air pollutant emissions in each of California's air basins in the 2030 timeframe (Figure 9).

California is geographically divided into 15 air basins of similar meteorological and physical conditions within which air resources are managed on a regional basis (California Air Resources Board, 2014). Because the SWITCH model makes new capacity investment/construction decisions at the spatial resolution of load areas and not exact locations in physical space, in order to re-aggregate emissions from portions of multiple load areas to any given air basin, I make the simplifying assumption that emissions from all generation associated with a given load area are distributed evenly across that load area. I re-aggregate average annual scenario emissions through area interpolation in GIS by calculating basin emissions as the sum of the spatially weighted contributions from the sub-load areas falling within each basin (J. Radke & Mu, 2000). Because the assumption of an even distribution of emissions across an entire load area is clearly unrealistic, these estimates should be interpreted as generalized characterizations. However, this additional analysis importantly demonstrates that the simulation and assessment method of forecasting the environmental effects of future energy scenarios developed herein is flexible enough to allow general characterization of those effects within more relevant spatial boundaries than load areas, if desired.

The results for the SunShot and LowNGprice scenarios in the 2030 time period are illustrated in Figure 9. I Find the LowNGprice scenario to have higher average annual emissions of all pollutants in the northern most coastal and inland air basins, as well as higher average annual NO_x emissions in the South Coast air basin in the area of Los Angeles. The SunShot scenario in turn has higher average annual emissions of all pollutants in the San Francisco Bay Area and San Joaquin and other inland central California air basins.

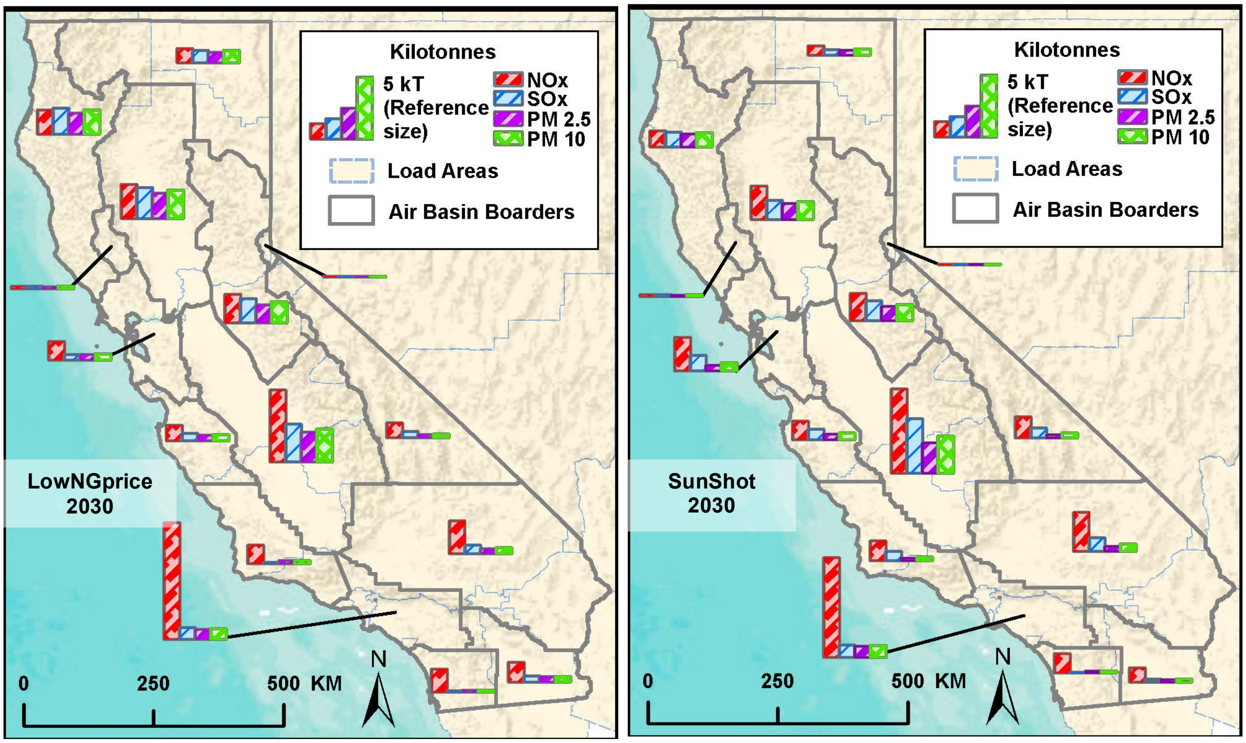

Figure 9. Estimated average annual emissions in California air basins in the 2030 time period for the LowNGprice (Left) and SunShot (Right) scenarios. (Base map data source: ESRI, USGS, NOAA)

B. WECC Water Consumption

Average annual WECC-wide water consumption for the six carbon reduction scenarios also follows a similar general trajectory through time. While average annual water consumption in the BAU scenario decreases between the present day and 2030 time periods, then increases thereafter, average annual water consumption for all of the decarbonization scenarios decreases steadily and remains below BAU over the entire period of analysis (Figure 10a, Figure 10b). Including water consumption associated with hydroelectric facilities (Figure 10a), average annual consumption ranges between 2000-5000 gigaliters (GL or 10^9 L) for all scenarios. Among the carbon reduction scenarios, the Limited Hydro scenario, with its inherent constraints on hydroelectric water availability, shows the lowest consumption through time. The remaining scenarios show similar levels of consumption through the 2030 time period and the LowNGprice scenario emerges with slightly higher consumption in, and after, the 2040 time period.

The water consumption associated with hydroelectric generation overshadows the consumption from other technologies in these results due to the high water consumption factor associated with reservoir evaporation. However, the consumptive water loss estimates reported by J. Macknick, Newmark, et al. (2012) for hydroelectric generators, and from which I derive the CFs for this analysis, associate all reservoir evaporation with power production and have a range of over 62,450 L MWh^{-1} (n=3). These estimates likely overstate generation-related water consumption given that for multiuse reservoirs, only a portion of the evaporation is attributable to power production (Jacobson, 2009; Lee et al., 2018; Mekonnen & Hoekstra, 2011; Pasqualetti & Kelley, 2008). In light of these implications, I focus the remainder of the results and discussion on water consumption excluding the contribution from hydroelectric generation. This is consistent with other studies such as that by J. Macknick, Sattler, et al. (2012) who elect not to consider hydroelectric withdrawal or consumption in there analysis of water use future energy scenarios due to the complexities in attributing water use to particular demands from hydroelectric reservoirs.

Excluding hydroelectric water consumption, average annual water consumption for the scenarios ranges between 300-900 GL and is more varied, particularly in and after the 2030 time period (Figure 10b). In the 2030 time period, variation in non-hydroelectric average annual water consumption among the scenarios stems from differences in levels of coal, gas, and geothermal generation (Figure 10c). But by the 2040 and 2050 time periods, this variation is driven largely by differences in gas-based generation (both with and without CCS infrastructure). In the 2050 time period there is also pronounced (but largely consistent) water consumption across all decarbonization scenarios associated with geothermal and solar CSP generation (Figure 10c). By the 2050 time period, I find the LowNGprice and SunShot scenarios have the highest (468 GL) and the lowest (323 GL) levels of non-hydroelectric average annual water consumption, respectively—a difference of more than 145 GL annually. The Base, CA50%RPS, and CADG scenarios are projected to require around 390 GL of non-hydroelectric water consumption annually (on average) by 2050, while the limited hydro scenario would require a slightly higher (non-hydroelectric) average annual water consumption of 413 GL.

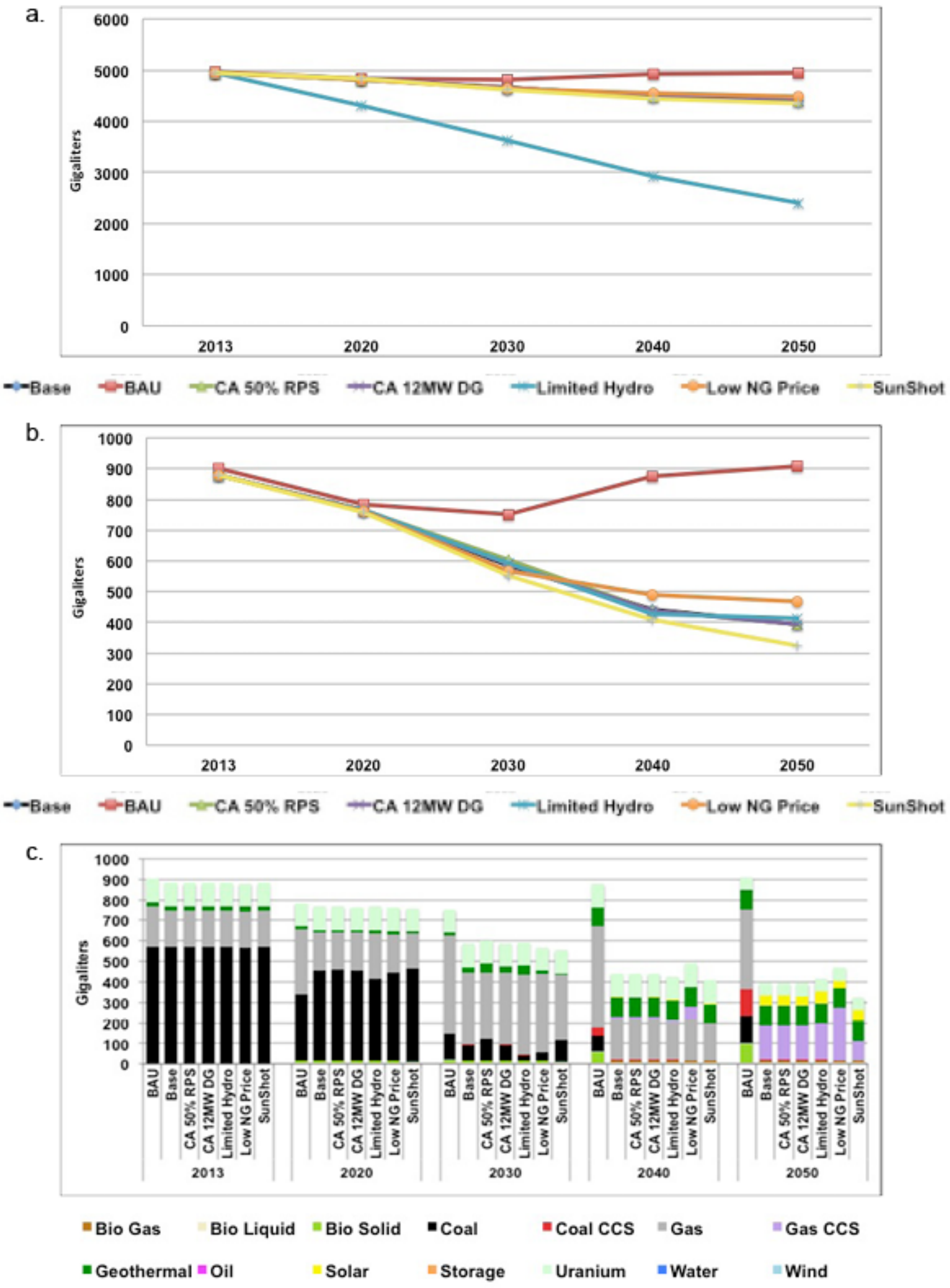

Figure 10. Total annual average water consumption in the WECC region by time period across scenarios. Hydroelectric water consumption is included in graph a, but excluded in graphs b and c. Graph c shows consumption by fuel type across scenarios in each time period.

The broad trends in water consumption observed in this analysis are largely consistent with the findings of other studies analyzing the potential water consumption associated with future low carbon electricity scenarios. For example, in their analysis of the water use implications of three future low carbon electricity scenarios for the United States, J. Macknick, Sattler, et al. (2012) also find that high renewable energy penetration scenarios lead to the most substantial reductions in water withdrawals and consumption. In a carbon reduction scenario with greater than 50% renewable penetration by 2050, they find consumption in 2030 for regions in the southwest is lower than their 2010 baseline values and lower than a scenario with the same carbon reduction goal but emphasizing coal CCS and nuclear technologies. Arent et al. (2014) similarly find that in a scenario with renewable energy production rates reaching 80%, thermoelectric water consumption could decrease by as much as 50% across the United States. Baker et al. (2014) conclude that renewable portfolio scenarios lead to overall reductions in water use compared to nonrenewable technology portfolios. The continuously declining trend in water consumption under all decarbonization scenarios found in this study is generally similar to that found by J. Macknick, Sattler, et al. (2012) but contrasts somewhat with that modeled by Chandel et al. (2011). J. Macknick, Sattler, et al. (2012) find (with a few exceptions) that across the carbon reduction scenarios they analyzed, consumption declines between 2030 and 2050 for regions in the southwest. Chandel et al. (2011) conversely find thermoelectric water consumption increases in the WECC under their carbon pricing scenarios, especially when CCS retrofits are allowed. However, they note that if electricity generated from wind and solar PV increases to 20% of the total generation, water consumption in their scenarios would decrease by 14–21%. This result is more consistent with some of the energy-water findings herein. Moreover, the higher consumption associated with the LowNGprice scenario in this study relative to the other decarbonization scenarios is driven by gas with CCS retrofits, which is consistent with the findings of Chandel et al. (2011).

I model the spatial distribution of average annual water consumption (excluding hydroelectric consumption) in the 2050 time period to analyze water consumption levels across the WECC region. Comparing load area consumption levels under the Base, SunShot, and LowNGprice decarbonization scenarios (Figure 11), I find load areas in the southwestern WECC and Canada tend to have higher annual water consumption than load areas in the rest of the region. These load areas generally experience the highest average annual consumption in the 2050 time period under the LowNGprice scenario, median consumption under the Base scenario, and median to low consumption under the SunShot scenario. The high average annual consumption levels under the LowNGprice scenario in this time period are largely driven by increased production from gas generators with CCS. There are exceptions however, including the Baja Mexico load area, where average annual water consumption in the 2050 time period is the highest under the SunShot scenario due to high levels of production from both gas generators with CCS and CSP generators. Furthermore, average annual consumption in the southwestern Arizona load area in the 2050 time period is the highest overall across all three scenarios due to production from nuclear and CSP generators.

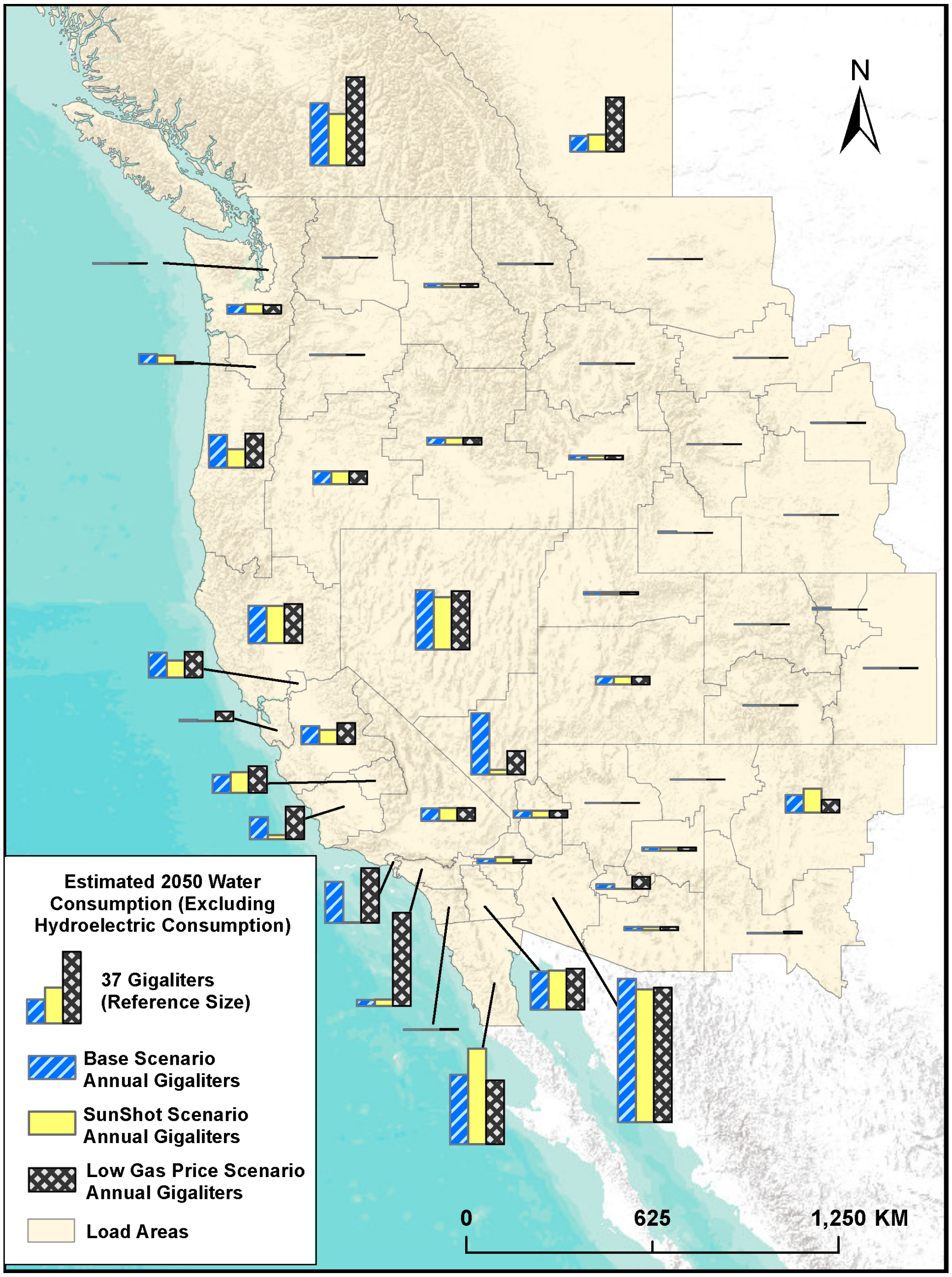

Figure 11. Average annual water consumption levels in 2050 in each load area across the Base, SunShot, and LowNGprice scenarios. (Base map data source: ESRI, USGS, NOAA)

C. WECC Land Use Conversion

In contrast to the declining average annual air pollutant and water consumption trends over time that I observe for the decarbonization scenarios, I find increasing land use conversion is required to support the WECC power system through time under such scenarios. This analysis focuses on new land use conversion; I do not quantify the land used for existing generation, storage, and transmission in the WECC. The increase in land use observed in this study is consistent with other studies which find modest (Arent et al., 2014) to significant (Kiesecker & Naugle, 2017; McDonald et al., 2009; Trainor et al., 2016) increases in land use conversion will be necessary across the United States to support low-carbon energy production in the future.

Figure 12a shows the incremental new land use conversion in each time period for the BAU and six decarbonization scenarios while Figure 12b and Figure 12c show the cumulative land use conversion required through time for these scenarios. By design, no new projects are built in the SWITCH model in the present time period. The incremental land use conversion (Figure 12a) required for newly built energy infrastructure in both the 2020 and 2030 time periods is relatively low and similar in all seven scenarios. Likewise, the cumulative amount of land use conversion required (Figure 12b) increases gradually and remains largely alike across scenarios through the 2030 period. In the 2030 time period, the cumulative land use conversion projected to be necessary for new energy infrastructure ranges from a low of approximately 194,000 ha^2 (under the CADG scenario) to a high of 246,000 ha^2 (under the BAU scenario). Beginning in the 2040 period, I find a large jump in the incremental land use conversion required for the decarbonization scenarios, leading to more variation in cumulative land use conversion as well. Incremental land use conversion for the BAU scenario in the 2040 period shows only a small increase from that required in the 2030 time period, but across the decarbonization scenarios the incremental increase in land use conversion required in the 2040 period is a factor of 5 to 8 times higher than the increment in the 2030 time period. This trend continues between the 2040 and 2050 periods, at which point I find the BAU scenario to require the least cumulative land conversion ($1.01x10^6$ ha^2) and the Limited Hydro scenario to require the most ($2.70x10^6$ ha^2). The LowNGprice scenario requires the least cumulative land use conversion of the decarbonization scenarios by 2050 ($2.20x10^6$ ha^2) while the base, SunShot, CADG, and CA50%RPS scenarios require similar amounts (approximately $2.3x10^6$ ha^2).

In the version of SWITCH used to model the scenarios analyzed herein, no new hydroelectric projects are constructed. Furthermore, new nuclear and solid biomass facilities are only allowed in the BAU scenario. I find the relative differences in cumulative land use conversion across scenarios are driven largely by variation in the amount of wind[36] and, to some extent, solar generation installed after 2030 (Figure 12c). For example, the Limited Hydro scenario requires the most new land use conversion of any scenario by the 2050 time period because it has more cumulative new wind power installed than any other scenario. Presumably this results from the need to meet the carbon emission constraint while having curtailed hydroelectric generation. Little land use conversion for new transmission ROWs is required in any scenario until after the 2030 time period. By 2050 I estimate the Base, CA50%RPS, and CADG carbon reduction scenarios require the highest amount of transmission related land conversion (all required 22,900 ha^2), while the SunShot scenario requires the least (approximately 15,700 ha^2).

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[36] As discussed previously, wind power is often characterized by the opportunity for multiple uses in the spacing between turbines and thus the land use conversion factor employed in this analysis, which reflects the entire area within the site boundary of a wind project, will overestimate the land use conversion required for such projects.

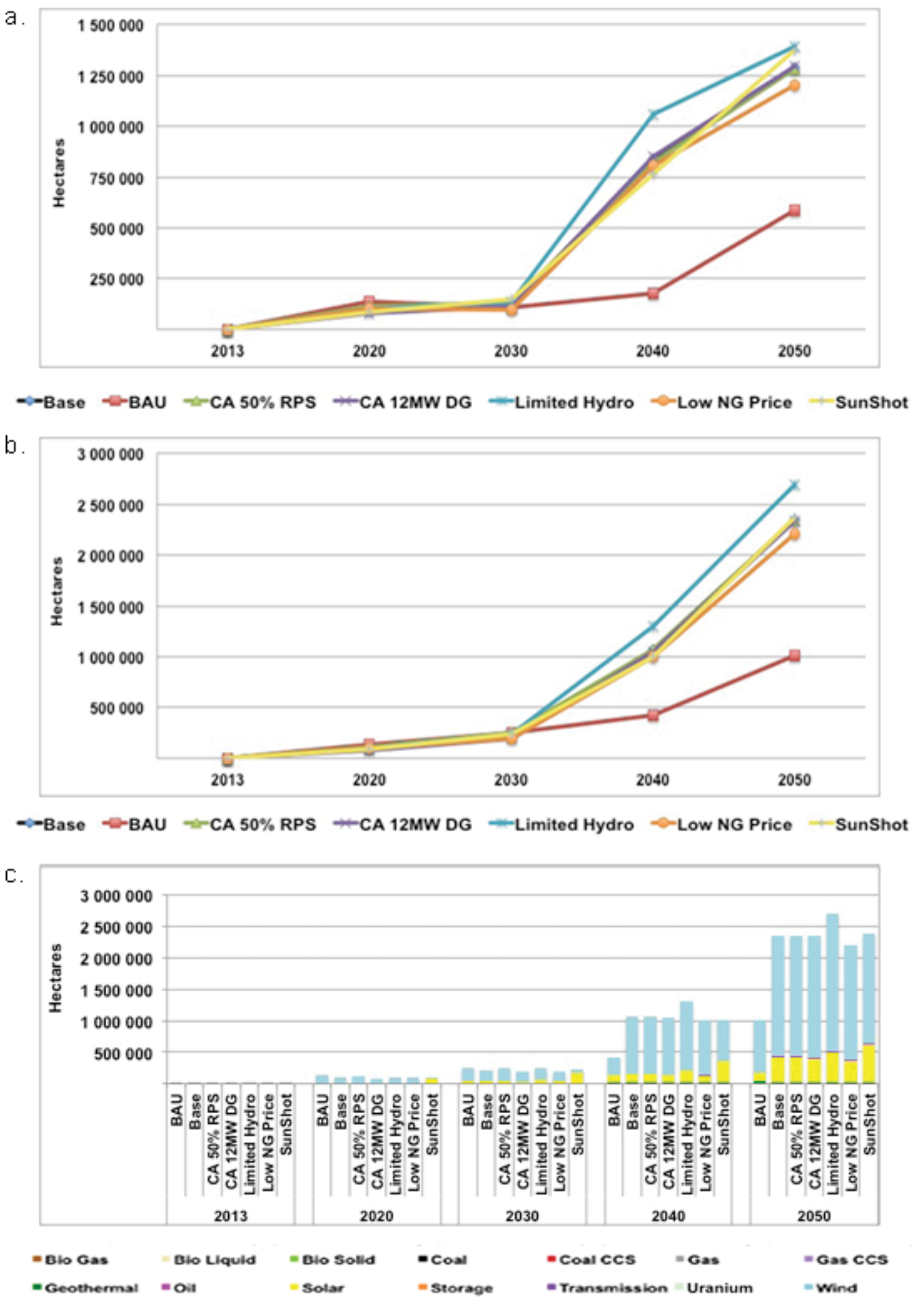

Figure 12. New land use conversion in each time period across scenarios, including: incremental land use conversion (graph a); cumulative new land conversion (graph b); and cumulative new land conversion by technology type (graph c). The technology types in graph c exclude water (as hydroelectric facilities are not built new in the SWITCH model) and include transmission instead.

I also model the spatial distribution of cumulative land use conversion by 2050 across load areas. I exclude from the spatial analysis the land requirements for transmission as transmission ROWs cross numerous load areas. Results for the Base, SunShot, LowNGprice, and Limited Hydro scenarios are compared in Figure 13. Land use conversion is highest in areas that favor wind development including Alberta, southeast Wyoming, and New Mexico. Within individual load areas, land use conversion is generally higher under scenarios that favor wind and solar development, such as the Limited Hydro and SunShot scenarios, and the lowest under the LowNGprice scenario.

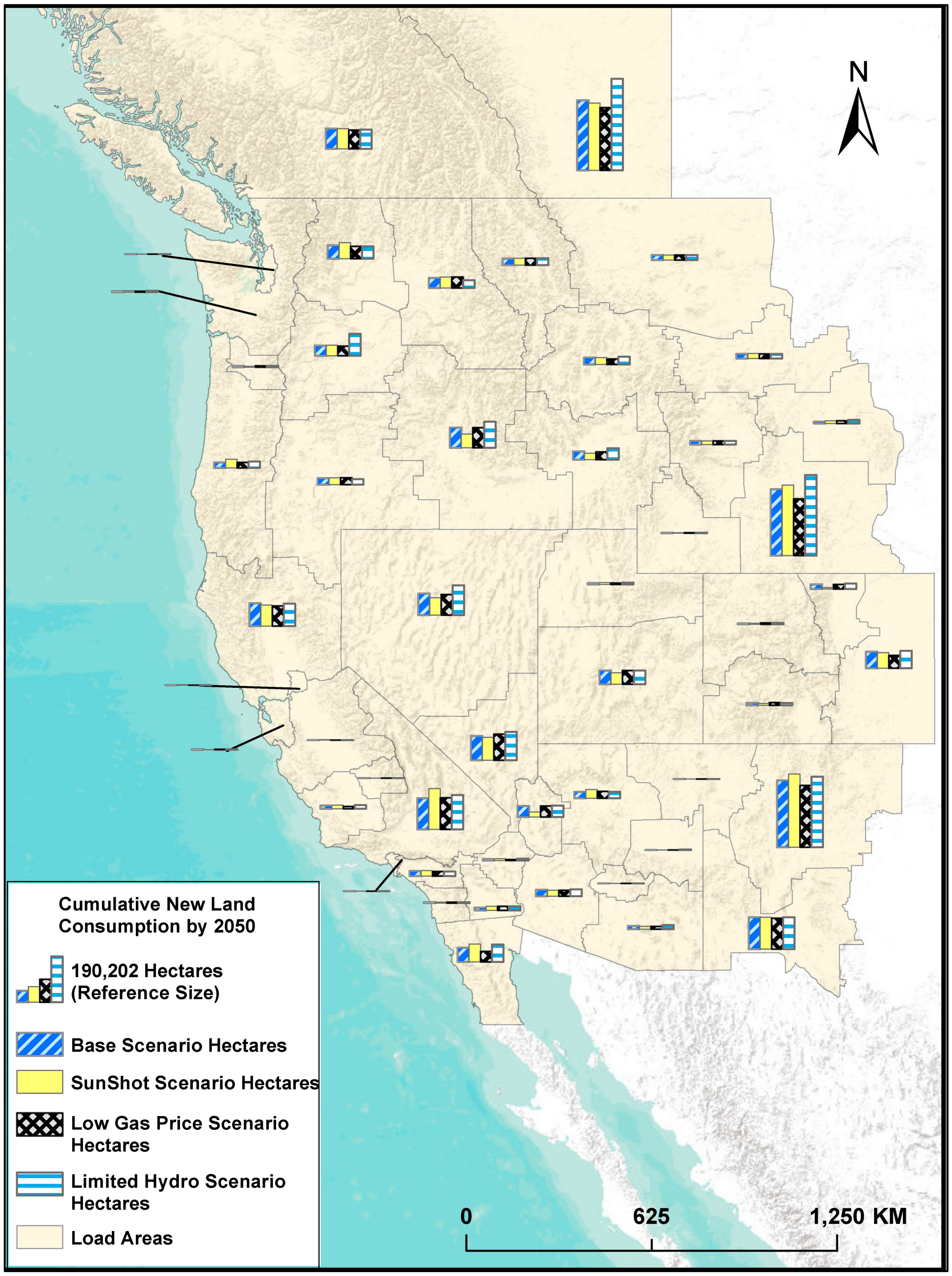

Figure 13. Cumulative new land conversion levels by 2050 in each load area across the Base, SunShot, LowNGprice, and Limited Hydro scenarios. (Base map data source: ESRI, USGS, NOAA)

IV. Discussion and Conclusion

Decarbonizing the electrical sector is essential to mitigating global environmental impacts from climate change, however, the choice of mechanisms employed to shift regional energy systems to low carbon options can greatly influence environmental benefits and costs at local and regional levels. In this chapter, I have shown that scenarios achieving the same level of carbon reduction under different policy conditions, economic incentives, or resource constraints can engender considerably different quantities and distributions of air pollution, water consumption, and land use conversion in a region given the varying influence of such constraints on future power system investment and operation decisions. While the effects of carbon emissions are global in nature, other potential environmental effects are location-specific and their consequences are likely to be of increasing importance in the face of climate change and population growth. In arid, agriculture-rich regions such as the western United States water resources are at a premium and may shift as the climate changes (Tidwell et al., 2013). Energy land uses often conflict with desires to preserve habitats and biodiversity (McDonald et al., 2009), aesthetics (Pasqualetti, 2011), and other land uses such as agriculture (Nonhebel, 2005). Moreover, pollutants like NO_x, SO_x, and PM are linked to pulmonary and cardiovascular health effects and have been implicated as short-lived climate forcing agents (Carmichael et al., 2013). Energy policymaking should be informed by these potential local environmental effects in order to avoid adversely undermining other significant environmental and social policy objectives.

Although this analysis focuses on the potential direct environmental implications of a low-carbon energy transition on resources in western North America, the simulation and assessment method presented herein is broadly applicable and the study conclusions are globally relevant. Many nations are currently exploring pathways to low-carbon electricity production, including scenarios similar to those I evaluate. While the impact factor assumptions employed in this analysis and the environmental consequences of the scenarios are regional in context, the results make clear that various decarbonization alternatives being widely considered internationally have the potential to result in considerably different quantities and distributions of environmental effects through time and space. Thus, it is imperative that policymakers carefully evaluate the environmental implications of these and other potential electricity sector decarbonization scenarios within the context of their own regions.

Kiesecker et al. (2017) argue that if planners and policymakers comprehensively viewed the big picture in advance of energy development, they could identify and help avoid conflicts that pit energy development needs against the value and long-term functional health of other natural resources. The realistic modeling of power system operation, expansion, and environmental impact patterns under potential decarbonization scenarios demonstrated here can aid policymakers and planners in achieving the goal of identifying and mitigating potentially unnecessary or inequitable environmental consequences of climate policies before they occur. In a simplistic example based on this analysis, I assume an equal weight for each class of impacts and rank the decarbonization scenarios evaluated in this chapter from lowest (1) to highest (6) impact in terms of WECC-wide average annual air pollutant emissions in 2030,[37] average annual

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[37] Annual air pollutant rankings reflect the ordering of scenarios based on their average rank positions across the four pollutants.

water consumption in 2050, and cumulative land use conversion in 2050 (Table 7). While no scenario stands out as the least or most impactful across all three categories, I find the CADG scenario, which reflects increased levels of small-scale DG in California, to have the lowest (best) average rank. This suggests that policy mechanisms encouraging distributed renewables may be most effective in minimizing the specific resource impacts evaluated here while also achieving deep decarbonization of the electricity sector in western North America to achieve climate change mitigation objectives.

Table 7. Rank order of decarbonization scenarios from lowest to highest pollutant emissions, water consumption, and land use conversion (*indicates a tie).

Rank	2030 Annual Emissions	2050 Annual Water Consumption	2050 Cumulative Land Use Conversion	Average Rank
1 (Low)	Limited Hydro	SunShot	LowNGprice	CADG (2.7)
2	LowNGprice	CADG	CADG	LowNGprice (3*)
3	SunShot	CA50%RPS	CA50%RPS	SunShot (3*)
4	CADG	Base	Base	CA50%RPS (3.7)
5	CA50%RPS	Limited Hydro	SunShot	Limited Hydro (4)
6 (High)	Base	LowNGprice	Limited Hydro	Base (4.7)

Additionally, evaluating the spatial distribution of environmental effects within and among scenarios can expose where impacts on different resources are likely to be uniquely or consistently prevalent across a region. This information is critical given that the location of an effect influences its consequences, as well as who bears or benefits from the result. For example, in this study I find consistently high air pollutant emission densities in California's Los Angeles load area across the decarbonization scenarios. Thus, the local population there may see little reduction in air pollution and related health impacts if electricity sector decarbonization proceeds under the evaluated mechanisms. Moreover, under the LowNGprice scenario the Los Angeles area additionally experiences high water consumption, suggesting this drought-prone region may experience little relief from power system water consumption under such a decarbonization scenario.

To maximize the environmental benefits of decarbonizing the electricity sector, policymakers should aim to guide the development of power systems based on local environmental impact reduction in addition to regional energy contexts and economics. One policy mechanism that could facilitate such development is the implementation of spatial feed-in-tariffs (FITs). FITs are an existing policy mechanism, notably used in Germany, under which long-term purchase agreements are offered for renewable electricity supplied to the grid from specific technology types. Under a spatial FIT policy, FITs would be implemented in specific geographic locations and apply to development of technologies that minimize both carbon emissions and local environmental impacts. The Los Angeles load area, for instance, could implement a spatial FIT for generation technologies with low air pollutant emissions and water consumption. Implementing such spatial FITs could also streamline project review and approval, speeding generation deployment, carbon reductions, and realization of environmental benefits in the associated areas.

The integrated power system simulation, multi-resource environmental impact assessment modeling approach I present in this chapter simulates the relative effects of electricity sector decarbonization scenarios and can inform policy decisions such that they maximize both carbon reductions and other environmental benefits. Yet, this analysis also has limitations. The results are based on the data and assumptions input into the SWITCH model, the scenarios analyzed, and the environmental impact factors utilized. I recognize that environmental impact factors can show large variation due to geographic conditions, boundary definitions, and measurement techniques (R. M. Horner & Clark, 2013; Mulder et al., 2010) and try to minimize this by focusing on direct impacts, clearly defining boundaries of the impact analysis, and utilizing impact factor source data that is as consistent as possible across technologies (e.g. source studies that provide factors across numerous technologies). Despite these efforts, the analysis is limited by the precision and resolution of available data. In terms of water use factors in the existing literature, Grubert and Sanders (2018) conclude the precision of available data is largely inadequate to support ongoing energy decision making. This analysis is also limited by my assumptions of static air pollution emission factors through time. Air pollutant emissions from power plants are likely to decrease in the future in response to existing regulations (Massetti et al., 2017) and with the evolution of combustion and emission control technologies. Thus the air pollutant emission results from this analysis are very conservative. Future analyses should capture and project trends in air pollutant emissions from WECC power plants and seek region- or sub-region specific impact factor data.

In the context of these limitations, I seek to validate this model by comparing the simulated water consumption for the 2013 (present day) time period to thermoelectric water consumption reported by Tidwell et al. (2011) for the year 2010. Tidwell et al. (2011) report that based on EIA and U.S. Geological Survey data, approximately 533 GL of water were consumed in 2010 for thermoelectric power generation in the portion of the WECC interconnection falling in the United States. In comparison, I simulate approximately 766 GL of non-hydroelectric water consumption from the portion of the WECC interconnection falling in the U.S. in the 2013 time period. These results are within the same order of magnitude and suggest my model can reasonably simulate observed conditions.

Finally, the implications of this analysis highlight numerous avenues for further study. For example, this analysis focuses solely on water consumption and air pollutant emissions from the operation of power plants, and land use conversion from construction of new power infrastructure. I would expect vastly different impact estimates from a full life-cycle analysis of energy supply options, which would include not only impacts from plant operation, construction, and decommissioning, but also those associated with relevant upstream and downstream processes in power production life-cycle such as fuel extraction, processing, and transport (Fredga & Mäler, 2010). Similarly, while I focus on the environmental implications of policies affecting the regional energy economy, there are numerous exogenous factors that strongly influence air pollution, water consumption, and land use conversion (e.g. vehicle emissions, agriculture, and urban growth), which merit consideration. While the version of SWITCH employed in this analysis assumes widespread electrification of vehicles, I do not model vehicular sector emissions directly. Nor do I incorporate water prices to evaluate the influence of water costs on power system investment, dispatch, and subsequent environmental impacts. These, too, are logical next steps for future research.

Chapter 4. Solar Sacramento: An Approach to Measuring the effect of Distributed PV Energy Generation on the Spatial Supply-Demand Balance Along the Electrical Grid and Simulating the Resulting Influence on Future Urban Development

I. Introduction

Energy infrastructure systems have played a significant role in shaping locations and forms of urban development over time, and today, driven by climate change concerns, a novel energy paradigm is emerging with a focus on producing electricity from low-carbon sources. A low-carbon energy future will require significant changes in the technologies and networks via which we produce and deliver electrical power—a fundamental infrastructure transition that will undoubtedly drive landscape transformation in the twenty-first century (Dale et al., 2011; Nadaï & van der Horst, 2010). Chapter 3 concludes that a scenario reflecting increased levels of small-scale distributed renewable generation in California (the CADG scenario) would be the most effective of those analyzed at minimizing air pollution, water consumption, and land use conversion while achieving climate change mitigation objectives for the electricity sector in western North America (Table 7). However, an increasingly distributed energy future can be expected to influence future patterns of urban development (Owens, 1986), which is arguably the most extreme type of environmental modification caused by humans (Dale et al., 2011; Melosi, 1990; Monstadt, 2009). According to the United Nations (2018), 68% of the world's population is expected to be living in urban areas by 2050, an increase from the 55% today that will likely have significant consequences for the environment. Despite these implications, very little contemporary work on low-carbon energy transitions focuses on the potential urban development consequences of such infrastructure change. In this chapter, I present an approach to quantifying the effect of a shift to distributed photovoltaic electricity generation on net energy consumption along the electrical grid in the City of Sacramento, California and simulating the resulting influence on the morphology of the city's future urban growth. I find that relative to a base growth scenario, a scenario emphasizing distributed rooftop PV integration could result in less mixed land uses in favor of diffuse single land use development, potentially in conflict with other objectives of sustainable urbanization. Thus, proactive energy and environmental planning must not only consideration of the direct natural resource impacts of any potential low-carbon energy transition, but also approaches to assess the complex urban development effects so that decision makers can consider the implications in the context of other sustainability objectives.

While decarbonizing the electric power sector necessitates a transition from the existing high-carbon system, the nature of renewable resources makes a spatial spectrum of divergent potential low-carbon energy solutions inherently feasible. Renewable resources such as solar and wind are at once both ubiquitous across the landscape and highly concentrated in specific areas. Thus, at one end of the spectrum, it is possible to construct large (utility-scale) renewable energy generators to capture concentrated renewable resources and transmit power long distances to consumers following the existing centralized electric power paradigm. Conversely, at the other end of the spectrum, the potential exists for a fundamentally different electricity supply structure involving numerous individual small-scale, distributed renewable energy generators situated at or close to points of consumption (Alanne & Saari, 2006; Burton & Hubacek, 2007; Wolsink, 2012). Neither scale of renewable energy generation seems wholly inevitable: some scholars suggest that massive, centralized power systems are too embedded to displace while others argue that trends in renewable energy technologies and cultural norms foreshadow a shift towards more decentralized power supply (Jiusto, 2009; Bridge et al., 2013; Carley & Andrews, 2012). There is also legitimate normative debate about the social, cultural, and environmental merits of centralized verses decentralized renewable energy futures (Bridge et al., 2013; Lovins, 1976). Because transition to low-carbon energy systems presents fundamental choices regarding what resources and generation scales to target, it is critical to consider the ways in which urban development may change under different future energy pathways.

Historically, the form of cities has, to a certain degree, reflected energy constraints or the lack there of. According to Bridge et al. (2013), at the urban scale, the low-carbon energy transition is challenging long-standing assumptions about city spatial form, the density of settlement, and even building design. Different low-carbon energy sources and the scale at which associated power-generating technologies are deployed (i.e. centralized vs. distributed) will impose unique constraints on spatial structure and may have very different consequences for urban development (Kirby Calvert & Simandan, 2010; Owens, 1979, 1986). Given these potential effects, Bridge et al. (2013) make a case for examining energy transitions as a geographical process involving the reconfiguration of current patterns and scales of economic and social activities, including urban development. While there is a general sense that future changes in the energy system are likely to influence urban development, there is considerable uncertainty about how urban form may respond (Jiusto, 2009; Owens, 1986).

To help reduce this uncertainty, in this chapter, I present an approach to simulating the influence of shifts in the location of electricity generation and net demand within the electrical grid on the morphology of future urban development. I use the City of Sacramento, California (Figure 14) as a case study and evaluate a scenario of increased rooftop solar photovoltaic energy production as a proxy for high penetration of small-scale, distributed renewable energy generation[38] more broadly. This approach involves a phased process of modeling meter-level energy demand; estimating rooftop PV technical potential at the building level; creating a topological model of the existing electrical distribution network; analyzing change in the spatial balance of energy demand and supply along network elements with the addition of distributed rooftop PV generation; and modeling future growth given these changes.

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[38] There is no consensus in the literature on a precise definition of distributed/decentralized generation, and the concept encompasses many technologies and applications (T. Ackermann, Andersson, & Söder, 2001; Carley & Andrews, 2012; Pepermans, Driesen, Haeseldonckx, Belmans, & D'haeseleer, 2005). In this case, I define DG to be an electric power generation source that is connected directly to the distribution network or on the customer side of the meter.

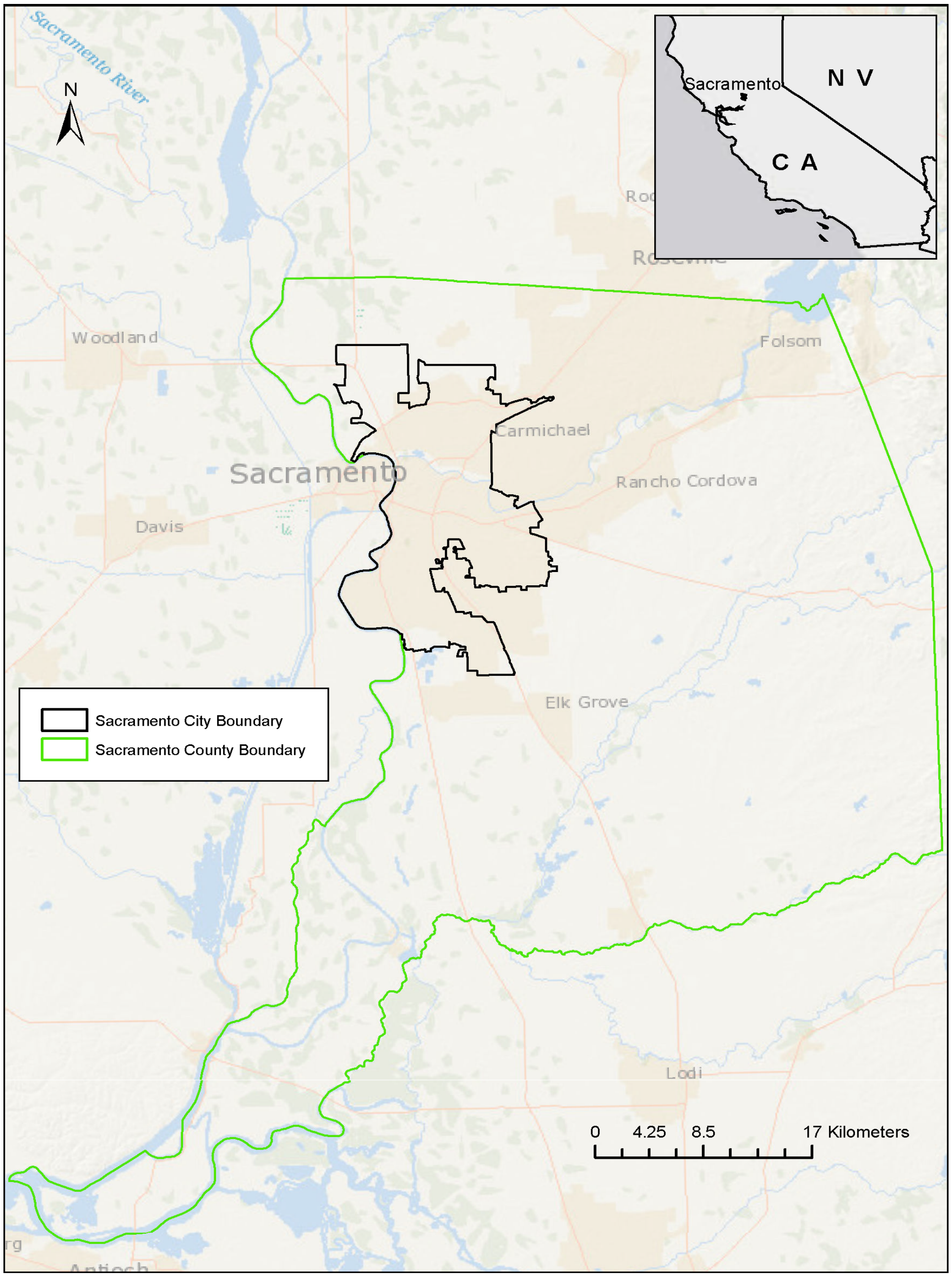

Figure 14. Sacramento County and Sacramento City areas. (Basemap data sources: Main: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, DeLorme, NGDC, and other contributors; Inset: Esri, DeLorme, NAVTEQ)

Contemporary work on potential low-carbon energy transitions has paid only limited attention to questions of renewable energy generation scale and distribution (Bridge et al., 2013), yet the ubiquity of renewable resources presents opportunities for generating power in distributed locations down to the individual property level. Distributed solar PV generation in particular is widely accepted and increasingly being adopted in many communities (Carley and Andrews, 2012). PV systems have the potential to aid in meeting urban energy demands (Boz, Calvert, & Brownson, 2015; Kammen & Sunter, 2016), and rooftops provide a large expanse of untapped area for solar energy generation (Castellanos, Sunter, & Kammen, 2017; P. Gagnon, Margolis, Melius, Phillips, & Elmore, 2016). Onsite DG could potentially alleviate congestion on urban grid infrastructures as well as reduce the costs and losses associated with the transmission and distribution of electricity by co-locating supply and demand (Boz et al., 2015; P. Gagnon et al., 2016). Nonetheless, modeling of future renewable energy scenarios has, until recently, focused primarily on centralized renewable energy technologies (Carley and Andrews, 2012). This work instead presents an innovative approach to modeling the effects on the net balance of energy along the network associated with co-locating DG supply at points of demand.

Moreover, while the need to decarbonize the energy sector is widely discussed today, the influence of such a transition on future urban development is rarely considered in environmental planning literature and practice (Todoc, 2008; Burchell & Listokin, 1982; Droege, 2006). A transition to distributed solar energy generation could significantly transform the location and balance of electricity supply on the distribution grid and facilitate changes in patterns of urban development by altering constraints on growth and redevelopment. However, Nguyen and Pearce (2013) argue that in the context of urban and regional development, centralized delivery of utility services still seems to be taken as given, and thus, there has been little research on the urban and regional development implications of transitions in utility provision paradigms. One exception to this is the work of Amado and Poggi (Amado & Poggi, 2012, 2014; Amado et al., 2017, 2018), who explore solar energy urban planning and seek to understand potential future urban design from a perspective of net-zero cities that balance energy supply and demand via aggregations of buildings. However, a better understanding of the effects of electricity supply transitions on future patterns of urban development is necessary to effectively formulate future adaptive energy and urban development policies (Amado et al., 2017; Wiginton, Nguyen, & Pearce, 2010). This research seeks to address that need.

Because individual energy and development choices are based on numerous social, economic, political, and technological factors (Kammen & Sunter, 2016; Melosi, 1985; Owens, 1986; Pasqualetti & Brown, 2014; Sachs, 2015; J. C. Williams, 1997), Owens (1986) cautions that changes in urban development may only result if energy system transitions are accompanied by other social and political shifts. As solar PV technologies have become more economically competitive, Nguyen and Pearce (2013) suggest that a new logic of infrastructure provision and a paradigm shift in energy policy to encourage distributed renewable generation have, in fact, begun to take hold. This seems to be the case in California, where distributed renewable resources have been a focus of state laws, and progress has been made in growing the state's distributed renewable capacity (California Energy Commission, 2018a). The California Solar Initiative (CSI; SB 1) was established in 2006 with an ambitious goal of installing 3,000 MW of distributed solar energy systems on new and existing residential and commercial sites by 2016. In 2011, Governor Jerry Brown endorsed a Clean Energy Jobs Plan that established a goal of adding 20,000 MW of renewable generation capacity in the state by 2020, with 12,000 MW coming specifically from renewable DG (systems up to 20MW and within the low-voltage distribution grid). At the end of 2017, more than 11,700 MW of DG capacity was operating or installed in California. This includes nearly 10,000 MW of distributed solar and 6,700 MW of behind-the-meter residential or commercial solar, which far exceeds the state's CSI goal. Given this success, in 2018, the state passed the "2019 Building Energy Efficiency Standards" (California Code of Regulations Title 24, Part I), which are new building codes mandating rooftop solar PV systems be included on all new homes starting in 2020 (California Energy Commission, 2018b).

Energy flows constrain and shape cities, and in the context of a broader societal shift toward low-carbon energy systems, there is a pressing need for approaches to understanding how the effects of a potential transition to distributed renewable energy generation may influence future urban development. Amado and Poggi (2014) suggest that a framework exploring future scenarios that simulate the widespread installation of PV systems and associated spatial changes in the urban context is particularly well-suited for developing such an understanding. This chapter demonstrates a novel approach to exploring how the spatial balance of electricity supplies relative to energy consumption along the electrical network might change under a scenario of widespread rooftop PV system deployment and how such changes may influence future patterns of urban development. The results of a case study applying this approach to the City of Sacramento show that the spatial balance of supply relative to consumption varies across the electrical network, and there are network elements, from meters to distribution feeders, where the PV technical potential exceeds consumption. Assuming these feeders are attractive to siting future land use development, and that areas with greater solar resources would be more desirable than those without, I demonstrate that relative to a base growth scenario, a distributed rooftop PV scenario would have both locally concentrating and regionally dispersing influences over future urban growth patterns. Furthermore, I show that mixed land uses decrease under such a scenario, and diffuse single land use development is favored. These results suggest that as cities continue to transition toward city-integrated renewable energy and smart grids, it is imperative that policymakers and planners understand how energy policies may influence future urban development patterns and the ability to achieve other urban sustainability goals.

II. Methods

Simulating the influence of distributed energy generation on patterns of future urban development requires a method of measuring how the spatial balance of energy supply and net demand may change within the electrical network, as well as a method of simulating the response of urban development patterns to those changes. In order to measure how the spatial balance of electricity supply and demand through the network may change, the approach I develop herein relies on meter-level electricity demand data for the Sacramento Municipal Utility District (SMUD) service area, estimates of PV technical potential electricity production modeled for the region in GIS, and a topological model of the SMUD electrical network I derive from utility-provided network connection data. I estimate the PV technical potential of suitable rooftop area across the City of Sacramento using Light Detection and Range (LiDAR) data, vector building footprint outlines, and an NREL geospatial model (P. Gagnon et al., 2016; Margolis, Gagnon, Melius, Phillips, & Elmore, 2017). Given the demand data and PV technical potential estimates, along with a topological network representation of the SMUD electrical grid I construct from the provided dataset, I quantify and spatially model in GIS the delta between energy demand and PV supply from the meter-level, through secondary and primary feeders, all the way up to the transmission substations. Using this approach, I identify to what degree (i.e. by how much) demand on any given existing feeder may be offset by distributed PV energy supply in this scenario and highlight those feeders where unchecked excess DG could flow into the next level of the networked system. To simulate the response of future urban development to these changes in the electrical grid, I use a topological model of the electrical grid with the data on degree of demand offset in a simple, rule-based urban growth model: UPLAN. I evaluate urban growth out to 2035 under a base scenario and a distributed rooftop PV scenario. I then compare the simulated future urban growth patterns between these two scenarios to understand how these patterns may change in response to a shift to decentralized solar photovoltaic electricity production.

Figure 15 illustrates the overall approach I take in this study, and the individual steps are described in more detail in the following subsections.

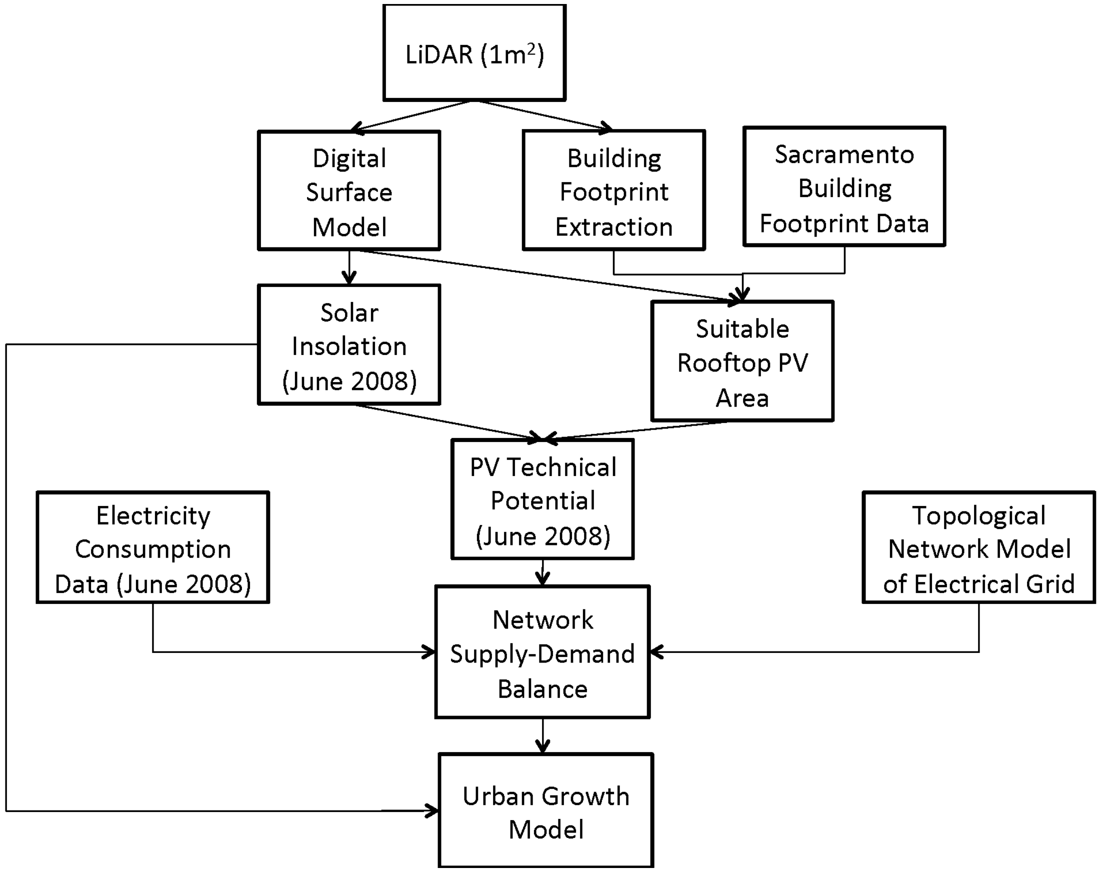

Figure 15. Flow chart of the overall process followed in this analysis.

A. Energy Demand Data

For this study, I obtain a dataset of historical, meter-level energy consumption (demand) data from SMUD. The SMUD was established in 1946 and is currently the nation's sixth largest publically-owned electric utility serving an area of 900 square miles and over 600,000 residential, commercial, and industrial customers in most of Sacramento County and small adjoining portions of Placer and Yolo Counties (Sacramento Municipal Utility District, 2018a). The SMUD was the first large California utility to receive more than 20% of its energy from renewable resources (Sacramento Municipal Utility District, 2018a) and maintains a robust research and development program focused on innovative and sustainable energy solutions (Sacramento Municipal Utility District, 2018c). The data I obtain from SMUD cover their service territory and include monthly electricity consumption at the meter-level for the year 2008; the latitude and longitude of meter locations; coded network interconnection data from each meter location up to the transmission substation; and existing PV system location and installed capacity data for 2008.

While the SMUD data set contains monthly consumption for an entire year, I focus this analysis specifically on electricity consumption data (and estimated potential supply) for the month of June 2008 to represent a situation when both electricity demand and solar PV production in the Sacramento area are likely to be near peak annual levels. I argue that a one-month time period is appropriate given the SMUD electricity consumption data is provided at a monthly resolution and because it is sufficient to demonstrate the approach developed herein without requiring excessive data processing time. Based on National Solar Radiation Data Base (National Renewable Energy Laboratory, 2016) average daily solar radiation data for each month of 2008 measured at the Sacramento Municipal Airport (Figure 16), I select the month of June 2008 as the focus of this analysis because it is the month of the year that Sacramento experienced the highest average daily global insolation. The summer months are also when SMUD experiences peak demand due to widespread use of air conditioners for space cooling in the face of high ambient temperatures (Sacramento Municipal Utility District, 2018b). According to the Sacramento Municipal Utility District (2018b), peak demand for energy in the summer currently reaches approximately 3,000 MW and requires the utility to be prepared to supply an additional 400 MW of electricity for approximately 40 hours a year. Thus, utilizing data from June 2008 approximates a situation where both electricity demand and solar PV technical potential in the Sacramento area are likely to be high.

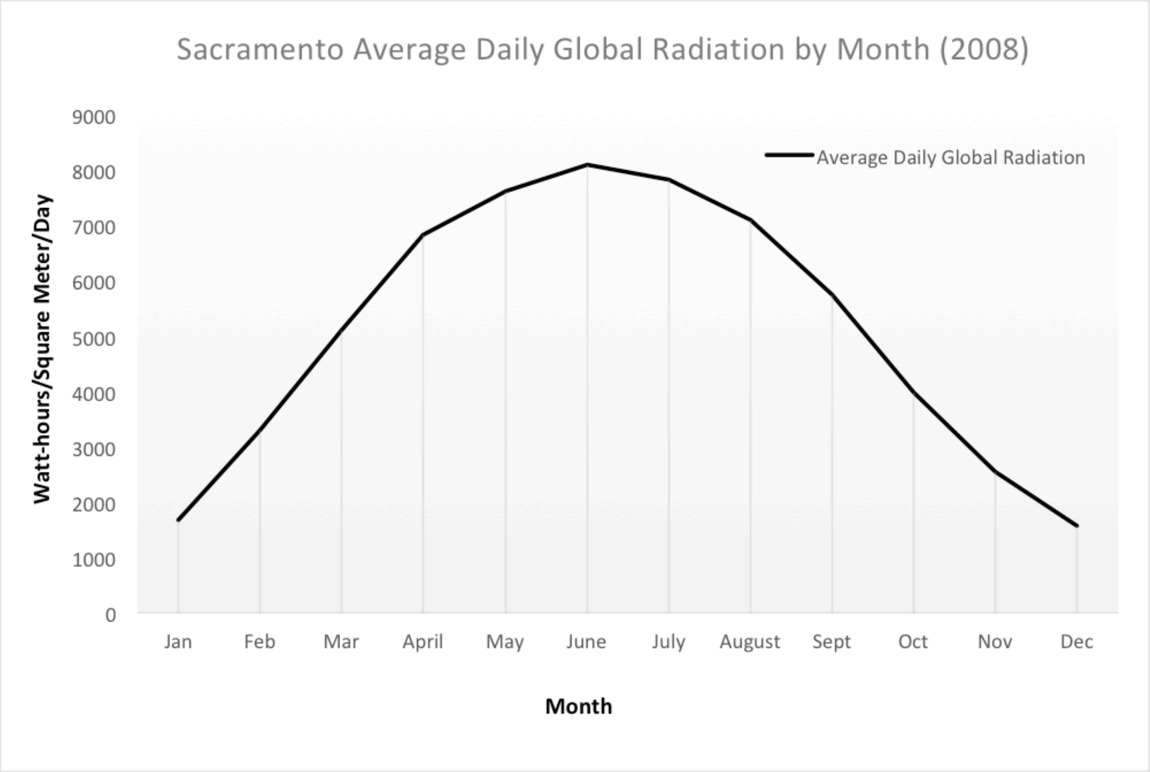

Figure 16. Average daily global radiation per month in 2008 as measured at the Sacramento Municipal Airport.

The SMUD dataset incudes 642,390 records representing individual meters across the SMUD service territory (approximately Sacramento County) with monthly consumption data for some or all of 2008. I pre-process the data to identify records with at least one non-zero day of consumption in June 2008. I find that 598,115 records (93%) have non-zero consumption in June 2008, and of these, 588,996 records have a full 30 days of consumption recorded for June 2008 (based on billing period dates included in the SMUD dataset). For those approximately 9,000 records that have some consumption in June 2008 but less than a full 30 days, I estimate a full month of consumption ($\mathrm{kWh}_{\mathrm{June30}}$) for each meter based on the average daily June consumption associated with the record (Equation 2).

Equation 2.

$$\mathrm{kWh}_{\mathrm{June30}} = \left[(30 - \mathrm{Days}_{\mathrm{JuneBill}})* \left(\frac{\mathrm{kWh}_{\mathrm{JuneBill}}}{\mathrm{Days}_{\mathrm{JuneBill}}}\right)\right] + \mathrm{kWh}_{\mathrm{JuneBill}}$$

I use the latitude and longitude data provided by SMUD for each meter to create a geospatial dataset of meter points across the region with their associated kWh demand for June 2008. Figure 17 illustrates the 30-day, June 2008 demand as a density surface interpolated from the June 2008 consumption values at the SMUD meter locations. The density surface was generated using Environmental Systems Research Institute's (ESRI's) ArcGIS "Optimized Hot Spot Analysis" tool which employs a kernel density function to illustrate the pattern of demand across the region as magnitude-per-unit area.[39] The mean monthly consumption is 1761.64 kWh ± 11355.54 kWh suggesting there is large variation in consumption values. This is to be expected given the diverse customer base covered by the consumption dataset. As illustrated in Figure 17, June 2008 energy consumption is highest per unit area (red and yellow colored) in the city proper, especially the city center, and is also relatively high in the portions of Sacramento County immediately to the northeast and south of the city boundary in the areas of Carmichael/Rancho Cordova and Elk Grove, respectively. The lower consumption density in the majority of the rest of Sacramento County (outside of the city bounds) can likely be attributed to the rural-residential and agricultural land uses in this area and the associated low data point density.[40]

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[39] The raster density surface has a cell resolution of 30 m (approximately 98 feet) and the kernel neighborhood used to generate the density values for each cell has a diameter equivalent to the optimal analysis distance identified for the hot spot analysis, in this case, approximately 724 ft (221 m).

[40] Note that the density surface values do not extend all the way to the southern county boundary because the SMUD dataset provided does not include any metered locations in that portion of the county, and the density surface includes “no data” values for cells which have no points in their kernel neighborhood.

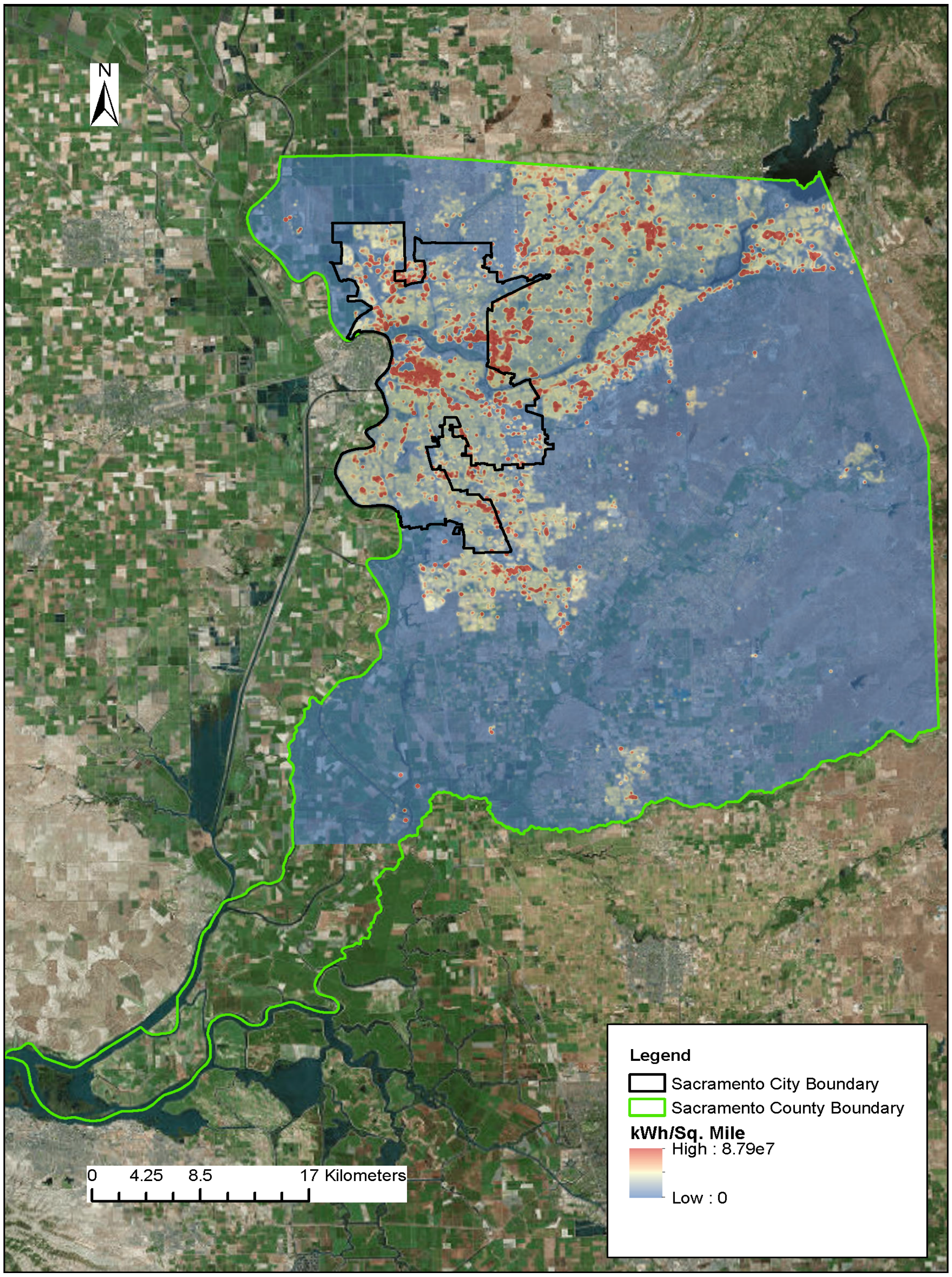

Figure 17. Kernel density surface of June 2008 demand interpolated from June 2008 consumption values at the SMUD meter locations. (Basemap data sources: Esri, i-cubed, USDA, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, and the GIS User Community)

B. Estimating Distributed PV Supply

To realistically compare electricity supply from potential distributed PV renewable generation to the June 2008 electricity consumption data, I identify rooftop areas that are suitable for solar system deployment and estimate their June 2008 solar PV technical potential. Technical potential is an established metric for renewable technologies that quantifies the generation feasible considering the primary energy source availability and quality, the performance of the technology capturing the energy source, and the physical area suitable for technology deployment (Brown et al., 2016; Lopez, Roberts, Heimiller, Blair, & Porro, 2012; Margolis et al., 2017).[41] Margolis et al. (2017) caution that technical potential does not consider economics or grid-integration factors, and thus estimates of the technical potential for a given area should be considered an upper limit of a technology's current potential generation, not a prediction of the expected deployment of a technology. However, I would argue that in the case of California, given the state's recent legislation requiring PV systems on all newly constructed homes beginning in 2020, the technical potential becomes an increasingly realistic measure of the expected deployment of PV systems.

There is a wide body of published literature on modeling the potentials (resource, technical, economic, market) of different types of renewable energies (solar, wind, water, biomass, geothermal) at different geographic scales (from the national scale to the scale of individual buildings). While beyond the scope of this study, a number of articles provide broad overviews of this body of work, the state of the art in modeling, shortcomings in existing methods, and avenues for future research (Angelis-Dimakis et al., 2011; K. Calvert, Pearce, & Mabee, 2013; Izadyar, Ong, Chong, & Leong, 2016; Resch et al., 2014). In general, this body of research recognizes GIS and remote sensing techniques as critical to examining renewable energy potentials given that theoretical potentials, conversion system locations and designs, and energy demand are highly sensitive to geography (Angelis-Dimakis et al., 2011; K. Calvert et al., 2013; Domínguez & Amador, 2007; M. W. Horner, Zhao, & Chapin, 2011; Resch et al., 2014).

A smaller yet robust subset of the broader body of research on modeling renewable energy potentials focuses more specifically on identifying rooftop area suitable for PV deployment and quantifying the associated technical generation potential at various geographic scales. Melius, Margolis, and Ong (2013) provide a review of methods to estimate rooftop suitability for PV based on 35 published studies and classify these approaches into three main categories: constant-value methods, manual selection, and GIS methods. Constant-value methods assume a certain percentage of building rooftop area is suitable for hosting PV and then extrapolate this to the total building stock (Margolis et al., 2017). Constant-value methods are computationally simple and are generally used to estimate the area available for PV at national (Denholm & Margolis, 2008; Vardimon, 2011) or regional (Wiginton et al., 2010) levels. Because studies in this group generalize rooftop characteristics, their results generally have low precision. Manual selection methods identify rooftop area suitability by manually evaluating individual buildings using tools such as manual digitization of building roof area from aerial photographs and calculating PV output using building-level calculators such as NREL's PVWatts Calculator (National Renewable Energy Laboratory, 2018). For example, Ordóñez, Jadraque, Alegre, and Martínez, (2010) use a manual selection approach to characterize rooftop area suitable for PV in Andalusia, Spain by manually identifying and digitizing a representative sample of rooftops. Manual methods are precise but time consuming, so they are difficult to replicate on a large scale

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[41] Three other types of potential often used to discuss energy technologies include resource potential (also called theoretical potential), economic potential, and market potential (Brown et al., 2016; P. Gagnon, Margolis, Melius, Phillips, & Elmore, 2016). Resource potential is the primary energy source potential in the area under consideration; economic potential is the quantity of potential generation that would result in a positive return on the investment of constructing the system(s); and market potential estimates the quantity of energy expected to be generated from the deployment of a technology in a market, considering policies, competition, and the rate of adoption (Brown et al., 2016; P. Gagnon et al., 2016).

(Margolis et al., 2017). To achieve higher precision than constant-value methods and efficiently cover large areas, the majority of studies take a GIS-based approach to identifying suitable rooftop area for PV deployment (Boz et al., 2015; Hong, Lee, Koo, Jeong, & Kim, 2017; Jakubiec & Reinhart, 2013; Kodysh, Omitaomu, Bhaduri, & Neish, 2013). These studies are distinguished by the fact that they automate the process of identifying suitable rooftop area by utilizing geospatial data and methods to select areas that meet desired characteristics (e.g. slope, aspect, contiguous area, etc.). Melius et al. (2013) cite a host of studies utilizing GIS approaches to determining suitable rooftop area and note that the majority use LiDAR[42] point data to model solar resource, slope, and aspect in order to estimate suitable rooftop area and potential energy generation.

Castellanos et al. (2017) provide an overview of studies for estimating urban rooftop PV potential in particular and categorize them through a slightly different lens, focusing on the scalability (how many cities are covered by an analysis) and resolution (the spatial resolution of techniques and results). Their low spatial resolution classification includes studies applying the constant-value methods described by Melius et al. (2013). According to Castellanos et al. (2017), medium resolution studies combine aggregated statistical data with spatially-resolved GIS and LiDAR approaches, for example Singh and Banerjee (2015). High resolution studies in their classification integrate geospatial methods for rooftop digitization and insolation calculations and take into account aspect and shading of buildings (Castellanos et al., 2017). Examples of such studies include Hong et al. (2017) and Jakubiec and Reinhart (2013). Comparing the deviation between a baseline, highly-generic, widely-applicable urban rooftop PV potential assessment methodology by the International Energy Agency with computationally intensive, highly-resolved techniques applied to the same areas, Castellanos et al. (2017) find large discrepancies in estimated PV rooftop potential. They conclude that existing generic (i.e. low spatial resolution) PV rooftop assessments may be too inaccurate to be used to inform policy designs.

In this study, I develop a high spatial resolution, GIS-based approach to determine PV technical potential of suitable rooftop areas in the City of Sacramento. This approach integrates LiDAR data and vector building footprint outlines of the Sacramento region into a geospatial tool developed by NREL for identifying rooftop area suitable for PV deployment (P. Gagnon et al., 2016; Margolis et al., 2017). Using the output rooftop area suitable for PV deployment at the building level and area solar insolation for June 2008 that I model in GIS from the same LiDAR data, I quantify the PV technical potential at the building level accounting for PV panel efficiency and performance of the additional system components (referred to as the performance ratio). I validate the resulting estimates against existing PV system installed capacity data from 2008 provided as part of the SMUD dataset. Finally, I post-process the modeled building rooftop area technical potential in order to assign consumption to individual meter points from the SMUD dataset. This approach in improves on existing methodologies by incorporating very high resolution, GIS-based analysis over a large region to produce a realistic, one-to-one connection of PV technical potential production and actual measured consumption at the individual building scale. By combining measured data with high-resolution geospatial modeling, and effectively

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[42] LiDAR data is remotely-sensed, high-resolution elevation data collected by an airborne collection platform and which can be used to make highly detailed geospatial elevation products of the ground, infrastructures, and vegetation.

analyzing every building in the study area as opposed to relying on sampling, this approach minimizes uncertainty in the results.

B.1 LiDAR Data

The approach I utilize in this study to estimate the technical PV electricity generation potential of building-level suitable rooftop areas employs LiDAR data for automated building footprint generation, identifying rooftop area suitable for PV system deployment, and modeling solar insolation.

For this analysis, I obtain a LiDAR point data and orthophotos covering the City of Sacramento and the surrounding area from the California Department of Water Resources (DWR). The data cover an area slightly larger than the City of Sacramento, but do not cover all of Sacramento County (Figure 18). The dataset is a subset of a larger LiDAR collection effort undertaken by DWR as part of their Central Valley Flood Plain Evaluation and Delineation (CVFED) project. The raw CVFED LiDAR data was collected in 2007 using an airborne collection platform on 34 flights. The raw data was collected with an average point spacing of 1-meter (m). The resulting point cloud dataset has a vertical accuracy of 0.18 m (0.6 feet (ft)) (1.96 x Root Mean Square Error (RMSE)z) and a horizontal accuracy of 1 m (3.5ft) (1.75 x RMSEx,y). The raw point cloud data was projected into the Universal Transvers Mercator (UTM) Zone 10 N, North Atlantic Datum (NAD) 83 (US foot) coordinate system and North American Vertical Datum (NAVD) 88. It was then post-processed for DWR to classify points, check data completeness and accuracy, and create tiles in LASer (LAS) file format. The subset of post-processed LiDAR point data I obtain for this study include 527 LAS tiles and 1741 orthophotos.

It should be noted that because the LiDAR data cover the City of Sacramento but not the whole county or extent of SMUD’s service territory, I identify suitable rooftop area and estimate the associated PV technical potential within the boundary of the city only. However, given the networked nature of the electrical grid, I include all meter locations and associated June 2008 consumption from the SMUD dataset when constructing a topological network representation of the electrical grid and evaluating the supply-demand balance along the grid.

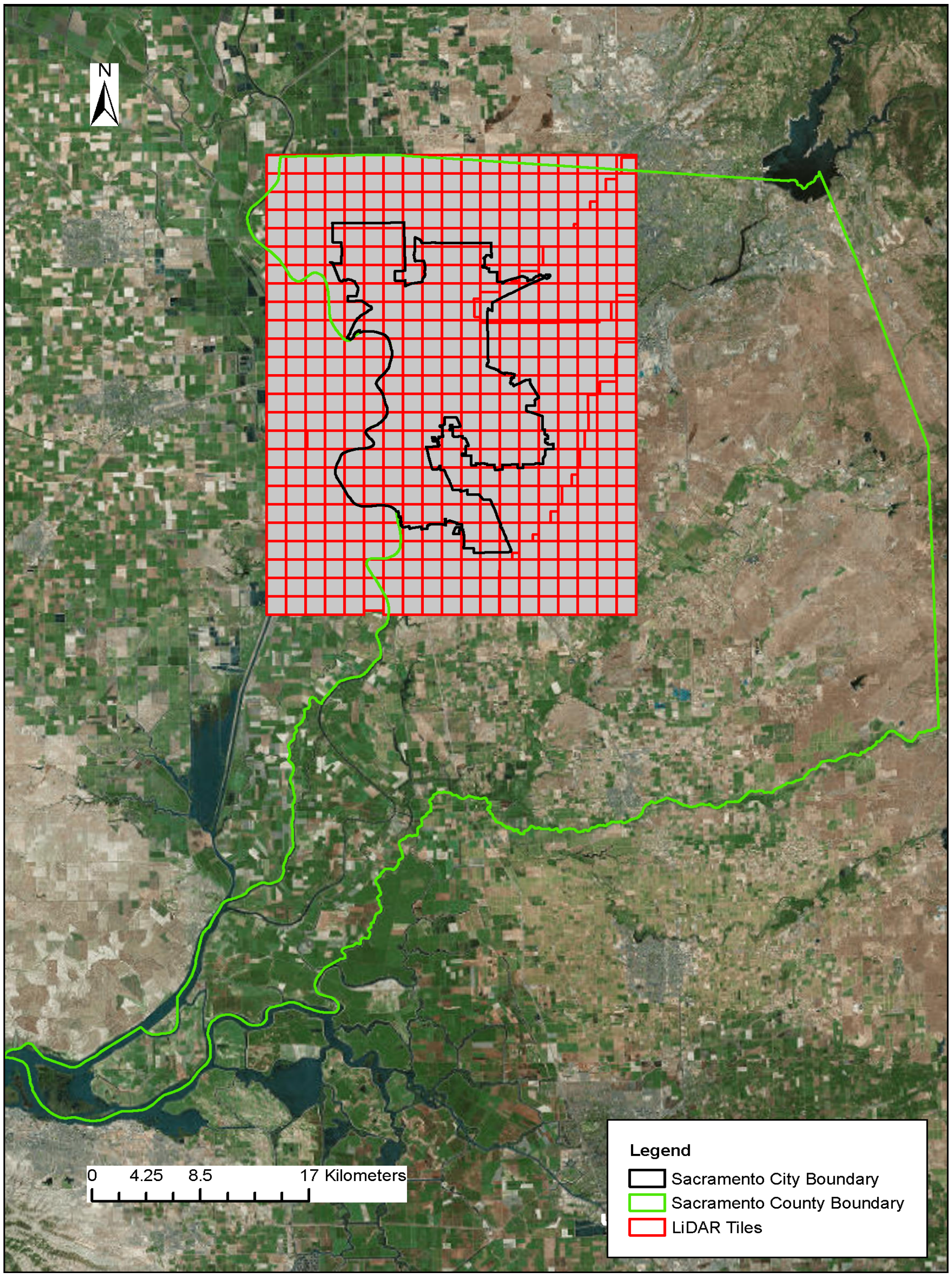

Figure 18. LiDAR point data coverage for the City of Sacramento and the surrounding area obtained from the California Department of Water Resources Central Valley Flood Plain Evaluation and Delineation (CVFED) project. (Basemap data sources: Esri, i-cubed, USDA, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, and the GIS User Community)

B.2 Building Footprint Data

In addition to LiDAR data, identifying rooftop area suitable for PV deployment using the NREL model (described below) requires a dataset of building footprints in the study region. In this context, a "building footprint" refers to a geospatial representation of the physical area occupied by a building, which is commonly represented as the outline of the perimeter (or roofline) of the building. In order to produce a complete dataset of building footprints for the region, I collect and utilize existing building footprint data where possible and otherwise generate footprints from LiDAR point data using a parameter-based tool called "Feature Extractor" (J. Radke et al., 2018). I then merge the collected and generated datasets to produce a single dataset of building footprints for the study area.

Existing Building Footprints

I obtain an existing dataset of polygon building footprints in the Sacramento region produced by the Sacramento County GIS unit (Sacramento County GIS, 2015). The data include building footprints of structures along the Sacramento Regional Transit corridor within a half a mile radius of Regional Transit stations or within one block on either side of railways. These data are represented in Figure 19 (left) below. This dataset covers a portion of the buildings in the City of Sacramento but is by no means complete. I was unable to identify additional existing geospatial datasets containing building footprints for the study area.

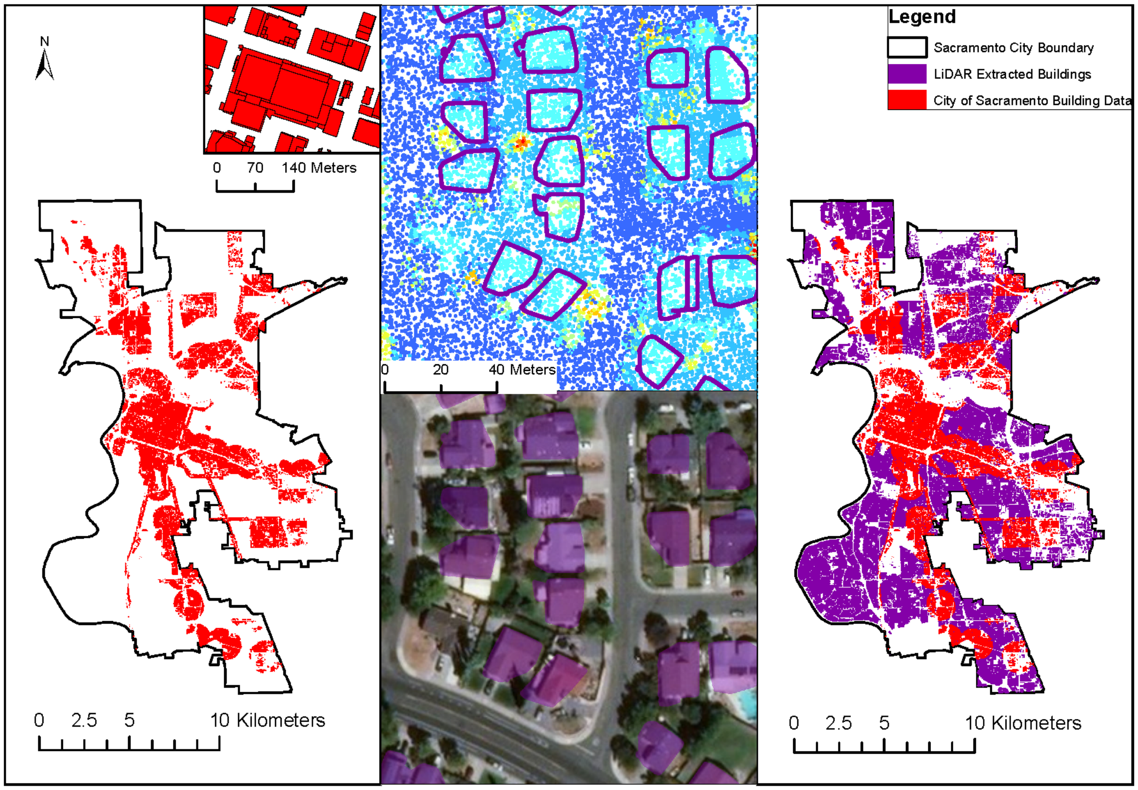

Figure 19. Building footprint datasets including obtained dataset from the County of Sacramento (left, in red) and building footprints derived from LiDAR data (middle top and bottom, in purple). The combined coverage for the City of Sacramento Region with both datasets is shown on the right.

Generated Building Footprints

In order to produce a complete set of building footprints for the study area, I generate additional footprints form the CVFED LiDAR point data using a parameter-based tool called "Feature Extractor." The Feature Extractor program automates the extraction of building feature shapes from LiDAR point cloud data based on a set of input parameter specifications provided by the user via a configuration file (J. Radke et al., 2018). These parameters are intended to guide the tool in extracting the desired building features and include maximum roughness of the building roof, maximum degree of roof slope, maximum and minimum angles that building walls can assume, building edge tolerance for overhanging trees, as well as optional parameters such as minimum and maximum building height, area occupied by a building, or minimum edge length, among others (J. Radke et al., 2018). The output from the Feature Extractor is a polygon shapefile of the features it extracts from the input LiDAR point cloud data.

I import the Sacramento LiDAR tiles in LAS format into the Feature Extractor program along with a configuration file containing pre-set parameters to generate the additional building footprints necessary for the Sacramento study area. J. Radke et al. (2018) use the Feature Extractor program to generate building footprints along the California coast and conclude that in order to create feature polygons that most accurately represent building outlines, LiDAR tiles corresponding to areas predominantly containing single-family residential or commercial buildings should be separated and run through the program with different configuration parameters. Thus, I manually evaluate the LAS tiles in the study area and classify them as either predominantly commercial or residential based on building types and run the resulting tile sets through the Feature Extractor separately. For both types of buildings, I accept the default Feature Extractor values for all parameters except roof surface roughness, maximum degree of roof slope, and tolerance for overhanging trees. I set the roughness and maximum slope parameters to the same values for both commercial and residential building tiles, but set the tolerance for overhanging trees for residential building tiles at nearly twice the value of that for commercial building tiles. Given that many residential buildings in the area have at least partially overhanging trees, I found this higher tolerance necessary for the program to successfully extract residential buildings. The footprint outlines and corresponding LiDAR point data for a residential area are illustrated in Figure 19 (middle top).

The building footprint polygons generated by Feature Extractor are close approximations of the actual building outlines (Figure 19; middle bottom). Although they do not match the exact footprints of the buildings, and the automated process does not capture a small fraction of buildings, based on visual inspection, they appear to be as or more accurate than other products, such as the recent national building dataset produced by Microsoft (Wallace, Watkins, & Schwartz, 2018) which appears to contain inaccuracies in dense urban and rural areas. I assure the quality and completeness of the dataset by loading the output polygon shapefiles from the building feature extraction process into a GIS, merging them together to a single extracted building footprint dataset, and performing post-processing. I calculate in GIS the perimeter, area, and perimeter/area ratio of each polygon in the extracted building footprint dataset then remove those polygons with a perimeter/area ratio of less than 0.24 to eliminate small spurious polygons from the extracted dataset. In order to focus further post-processing only where necessary, I use the meter points from the SMUD dataset in combination with geospatial parcel data downloaded from the County of Sacramento (Sacramento County GIS, 2016) to select parcels in the city boundary that contain one or more SMUD meter points. I then select by location from both the existing and extracted building footprint datasets only those building polygons that intersect parcels with SMUD meter points. I select by location and erase any footprints from those remaining in the extracted dataset that overlap footprints from the obtained Sacramento footprint dataset, as I assume the obtained Sacramento footprints are more accurate than the extracted footprints. I then merge the extracted and obtained building footprints into a single dataset of building footprints for all parcels in the city that contain SMUD meter points. Finally, I assure the completeness and quality of the footprint dataset by reviewing the identified parcels overlaid on the orthophotos from the CVFED dataset to ensure that all buildings intersecting those parcels are accurately represented. I manually digitize or edit the footprints of buildings that were not captured through automated feature extraction or appear highly inaccurate. I then combine the Sacramento County and extracted building footprint datasets to produce a dataset covering the City of Sacramento (Figure 19; right).

B.3. Identifying Rooftop Area Suitable for PV Generation

I use a recent NREL geospatial modeling tool developed by P. Gagnon et al. (2016) to identify the specific area(s) on any given rooftop that are suitable for deployment of solar PV generation technology. The actual rooftop area suitable for PV deployment will be less than the total rooftop area given the orientation, shading, and constraining features of different parts of a roof as well as building code setback requirements (Kodysh et al., 2013; Mainzer et al., 2014). Utilizing high resolution LiDAR data, GIS-based studies can identify sub-rooftop areas that are suitable in terms of orientation, slope, size, and which avoid constraints such as ventilation systems, chimneys, skylights, and antennas. The NREL methodology I employ in this approach identifies suitable rooftop area for PV deployment based on shading, orientation, slope, and contiguous areas of consistent elevation and aspect.

The NREL methodology is discussed in detail in a number of publications by the developers (P. Gagnon et al., 2016; Margolis et al., 2017; Melius et al., 2013) and scripts that can be used to execute the tool in ESRI's ArcGIS software can be accessed at http://maps.nrel.gov/pv-rooftop-lidar. Inputs to this tool include a building footprint dataset, raster digital surface model (DSM) representing study area elevations, and a vector polygon delineating the study area. I utilize the final building footprint dataset described in section B.2 for the building footprint input. I produce a 1 m^2 resolution raster DSM from the DWR LiDAR point cloud data obtained for this study using ESRI's ArcGIS software.[43] A DSM is an elevation model that represents the elevation of the first object detected by a laser pulse and generally includes above-ground objects such as tree canopies and buildings. Utilizing these inputs, the NREL tool produces a final data set containing the area suitable for PV deployment on every roof within the building footprint dataset.

The NREL methodology combines the DSM along with the building footprint data to identify suitable rooftop area for PV deployment based on shading, orientation, slope, and contiguous area. The tool analyzes seasonal variation in shading across rooftops by running ESRI's "Hillshade" tool for four calendar days, March 21, June 21, September 21, and December 21, then averaging the hours of sunlight per square meter across these days. Next, the tilt and azimuth for each square meter of roof area are calculated using ESRI's "Slope" and "Aspect" tools and northwest, north, and northeast facing areas are removed as unsuitable for PV development. The aspect data is then run through a variety function, which returns the number of different values in a 3×3 neighborhood surrounding each square meter of roof area. Any cell bordered by more than three unique azimuths in the 3x3 window is excluded to remove areas of

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[43] To create a DSM in ArcGIS I import the CVFED LAS data files to create a LAS Dataset (.lasd) in ArcGIS, apply a LAS filter to select the points classified as first returns, and then run the "LAS Dataset to raster" tool with the elevation data from the LAS points as the values to be used for the raster output. I select binning interpolation with the maximum elevation value as the cell assignment type and a natural neighbor void fill method when creating the DSM raster.

changing roof orientations and excessive noise. Using the remaining aspect data, the tool aggregates contiguous areas of identical orientation class on a rooftop into polygons representing contiguous roof planes. The aspect, average slope, and average shading of the cells falling within a roof plane polygon are spatially joined to that polygon. Roof plane polygons are then analyzed and removed as unsuitable if they do not meet shading, slope, or size criteria. In terms of shading, P. Gagnon et al. (2016) estimate the number of hours a rooftop would need to be in sunlight to produce 80% of the energy produced by an un-shaded system of the same orientation in the same city. For Sacramento, this value is 20.68 hours. Roof plane areas that do not meet this shading criterion are excluded from the dataset. Additionally, all planes with slopes greater than 60 degrees or contiguous projected horizontal footprint of less than 10 m^2 are removed from the dataset as unsuitable.[44]

The suitable rooftop area output from my application of the NREL model for the parcels with SMUD demand data in the Sacramento study area is shown in Figure 20. In a few instances, buildings and suitable rooftop areas cross parcel boundaries. Thus, I intersect the suitable rooftop area polygons with the parcel polygons to divide any suitable rooftop areas that cross parcel boundaries by those parcel boundaries. This facilitates later attribution of production to individual parcels.

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[44] An area of 10 m^2 is sufficient to install a 1.6 kW system, assuming a 16% efficient panel, and represents a conservative lower-end estimate of viable PV system size, based on current PV performance and historical patterns in reported PV system sizing (Margolis et al., 2017). Similarly, slopes of greater than 60 degrees were deemed unsuitable for PV systems by Margolis et al. (2017) based on discussions with solar PV installers.

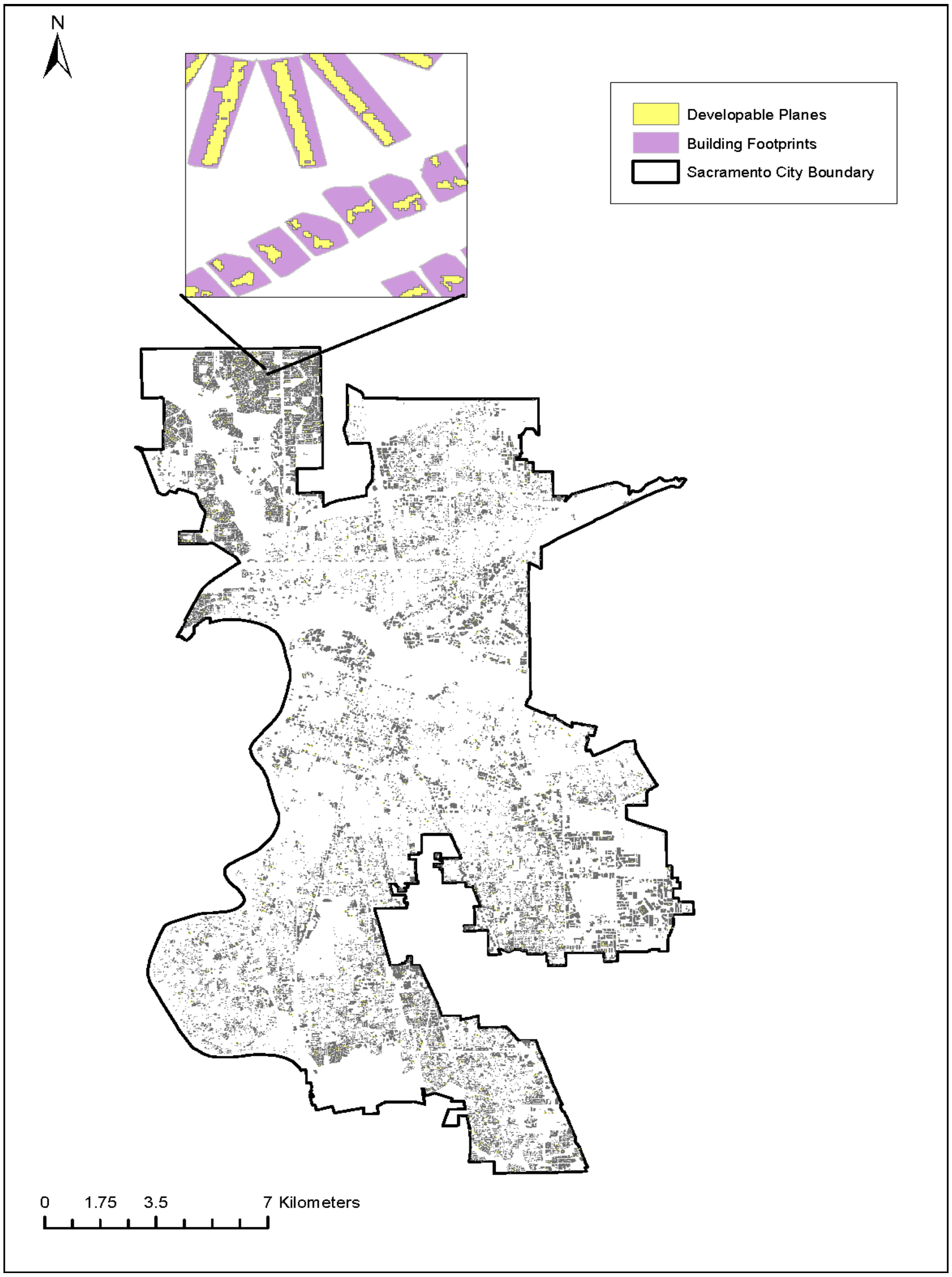

Figure 20. Suitable rooftop area for solar PV development modeled using the NREL geospatial tool from P. Gagnon et al. (2016).

Validation of Modeled Rooftop Area for PV Deployment

Validation can be a major challenge and few studies of suitable rooftop area for PV include a process for validating the particular rooftop-area estimation method (Freitas, Catita, Redweik, & Brito, 2015; Melius et al., 2013). Validation methods for such studies also vary widely in scale and type, with some studies validating against other computer models, some against existing solar resource data, and others by physically inspecting actual buildings (Melius et al., 2013). Melius et al. (2013) validate the NREL modeling method against 205 actual PV systems across three states and find the model predicts a developable area that is at least as big as the installed system (based on physical measurement) 79% of the time.

In order to evaluate the accuracy of the modeled rooftop PV area in this analysis, I compare the modeled suitable rooftop area to know installed system capacity data for certain metered points as reported in the SMUD dataset. There were approximately 2400 metered accounts associated with an installed PV system in the City of Sacramento in 2008 according to the SMUD data. I identify 45 meter points (accounts) that had installed PV systems in Sacramento City proper in 2008, have suitable rooftop area for PV development based on my modeling, and which fall on parcels having non-zero June 2008 demand with a single, metered account (one metered consumption point as opposed to multiple). I convert the modeled suitable rooftop PV area for the buildings on these parcels to installed capacity assuming a ratio of 10 m^2 / 1.6 kW per Margolis et al. (2017). I then compare the modeled installed capacity to the actual installed capacity associated with the same meter from the SMUD dataset. The average absolute difference between the modeled and actual installed capacity was 3 kW± 3.8 kW. Approximately 69% of the modeled capacities were at least as large as the actual installed capacity, and 31% were smaller than the actual installed capacity. This percentage is similar to but slightly less than that found by Melius et al. (2013). The discrepancy in the modeled vs. installed capacity stems, in part, from the fact that the approach here is focused on technical potential not economic potential. Technical potential captures the maximum suitable installed capacity based on physical factors, while economic potential (return on investment) is likely a greater factor in sizing actual installed PV systems. Thus, I would expect the modeled installed capacity to be larger than the actual installed capacity more often than not. Additionally, this validation should be considered in the context of the fact that I use a back-of-the-envelope ratio to convert modeled suitable PV area to installed capacity as opposed to measuring system area in situ.

B.4. Solar Insolation and PV Technical Potential

Each of the suitable rooftop area polygons derived in this analysis can be thought of as an individual rooftop solar power system. Calculating the technical potential of each system requires an estimate of the incoming solar radiation (insolation) that reaches the rooftop surface (i.e. the resource potential), as well as accounting for the performance efficiencies of the PV system. While the radiation entering the earth's atmosphere from the sun is relatively constant, the radiation that actually strikes a given rooftop on the earth's surface is more variable due to seasonal variations in intensity, weather, atmospheric conditions, shading from adjacent topography and surface features, and individual building characteristics (Kodysh et al., 2013). For real topographies, purely physical solar radiation formulations cannot compute surface radiation that accounts for obstructions to sunlight; this instead requires computational modeling of the physical context of a complete urban environment to account for intricate shadowing events and building facades (Freitas et al., 2015). Given this, I model insolation across the study region in GIS using the 1 m^2 DSM produced for this study. I model insolation for the entire month of June 2008 to match the demand data used for this analysis. The output of the insolation model is a 1 m^2 resolution raster containing the incoming solar radiation incident on each cell for the month of June 2008. I then use this data to calculate the estimated power output for the month of June 2008 from each suitable rooftop area accounting for solar panel efficiency and an average performance ratio.

Solar Insolation

To calculate solar insolation across the study area, I use ESRI's "Area Solar Radiation" geospatial model (Environmental Systems Research Institute, 2017; Fu & Rich, 1999). Geospatial area-based models such as this tool, estimate solar radiation intensity for each cell using a DSM of the entire geographical area to account for shading from surrounding features, as well as building characteristics including slope and orientation (Kodysh et al., 2013). Freitas et al. (2015) conduct a review of methods for modeling solar potential in the urban environment and cite numerous published studies of solar resource availability that employ ESRI's Area Solar Radiation model given its accuracy, calculation speed, and temporal and spatial resolution flexibility. According to the modeling and validation of rooftop solar radiation by Kodysh et al. (2013), area-based spatial solar radiation models are desirable for the creation of highly accurate rooftop solar radiation maps, and ESRI's Area Solar Radiation tool is suitable for fine scale studies of rooftop PV potential.

The Area Solar Radiation tool implements a comprehensive geometric solar radiation model that calculates insolation maps using digital elevation data and highly optimized algorithms to account for the influences of the viewshed, surface orientation, elevation, and atmospheric conditions at a given location (Fu & Rich, 1999, 2002). The general methodology is briefly summarized here, but is described in detail by Fu & Rich (1999, 2002). This model generates an upward-looking hemispherical viewshed based on a DSM; splits the sky into different sectors defined by their zenith and azimuth coordinates; considers either a uniform overcast sky with the same incoming diffuse radiation from all sky directions, or a standard over cast diffuse model, where diffuse radiation flux varies with zenith angle; and determines sky obstruction and total incoming solar radiation for a given location based on viewshed, sunmap, and skymap calculations (Freitas et al., 2015; Fu & Rich, 1999; Kodysh et al., 2013). Given that cloud cover, precipitation, dust, and other atmospheric conditions may attenuate the amount of diffuse and direct solar radiation for a given surface, a user-defined atmospheric transmission value (transmittivity)[45] is used in the model to capture these effects (Kodysh et al., 2013). The output of the model is a raster grid with each cell's value representing a realistic estimate of the incident solar radiation at the surface location represented by that cell.

I model insolation across the Sacramento study region using ESRI's Area Solar Radiation tool with the 1 m^2 DSM produced for this study as the elevation model input. Relevant user-specified model parameters include sky size (number of cells in the viewshed), time configuration, diffusion model type, and transmissivity factor. For this analysis, I utilize the default sky size of 200, which means viewshed calculations are performed within a 200x200 square neighborhood around the cell for which a calculation is being made. I set the time configuration to the entire month of June 2008 to match the duration of the demand data used for this analysis. I select a uniform sky diffusion model, which assumes a uniform overcast sky with the same incoming diffuse radiation from all sky directions, and set the transmissivity at 0.5 to represent a partially clear sky. Because the Area Solar Radiation tool takes into account the slope of the building

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[45] Atmospheric transmittivity is defined as the ratio of the energy received at the upper edge of the atmosphere to that reaching the earth's surface by the shortest path (in the direction of the zenith), averaged over all wavelengths (Kodysh, Omitaomu, Bhaduri, & Neish, 2013). Values range from 0 (no transmission) to 1 (complete transmission) with 0.6 or 0.7 representing very clear sky conditions and 0.5 for a partially clear sky (Kodysh et al., 2013).

rooftop in calculating insolation at the surface, the insolation values derived here assume the tilt angle of a solar PV panel is parallel to that of the roof plane on which it occurs. This is a simplifying assumption I make for this analysis, and it may not always be the case, especially for systems installed on flat rooftops where panels are often tilted at an angle that maximizes PV output (Mainzer et al., 2014).[46] The resulting 1 m^2 raster of the estimated incoming solar radiation (in Watt-hours (Wh)/m^2) across the study area during the month of June 2008 is shown in Figure 21.

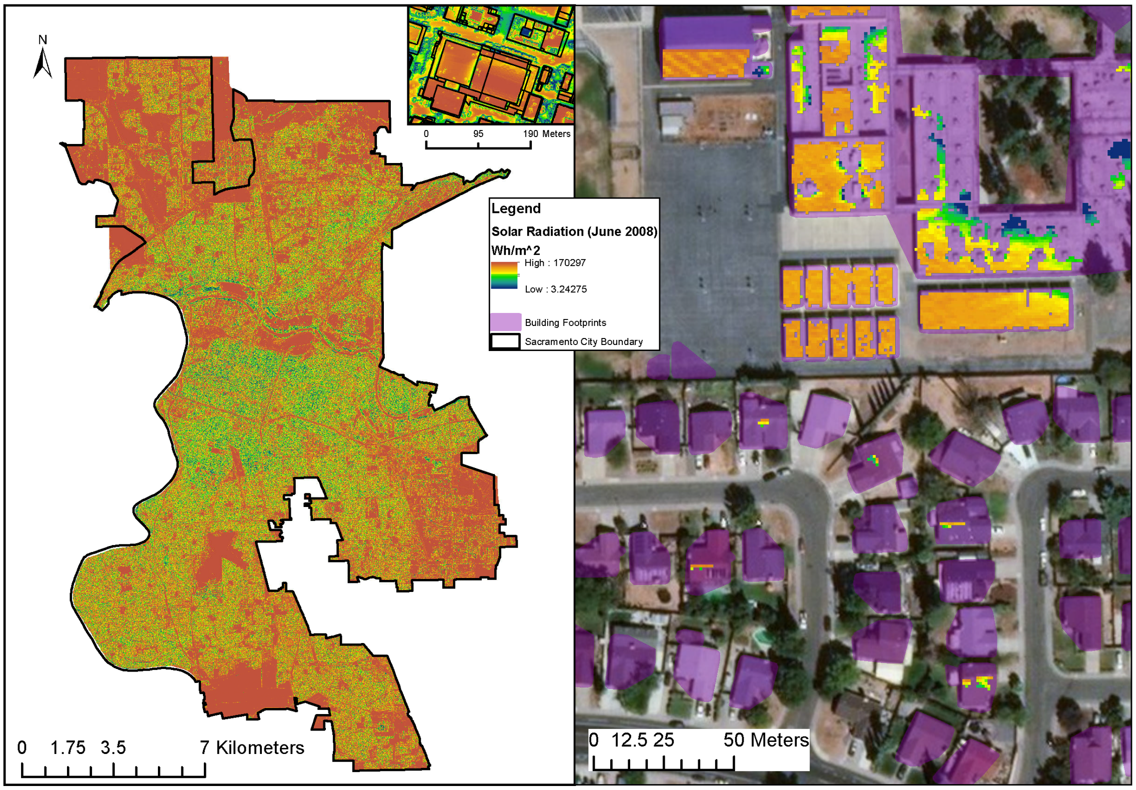

Figure 21. June 2008 Solar Radiation modeled across the City of Sacramento at a 1 m^2 resolution (Left) and clipped to suitable rooftop area polygons in a representative area (Right).

Technical Potential

To estimate the solar PV output for the month of June 2008 for each polygon of suitable rooftop area (i.e. each individual system), I calculate the incoming solar radiation incident within each polygon then multiply that value by a solar panel efficiency factor (ηPV) and performance ratio (ηPR; also referred to as a derating factor) which I derive from values reported in the literature. In a GIS, I clip the insolation raster using the suitable rooftop area polygons (Figure 21) and then use ESRI's "zonal statistics as table" tool to sum the insolation values of the raster cells falling within each suitable area polygon (Wh_i). I make the simplifying assumption that panels are

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[46] Other studies have assumed the same optimal fixed tilt for all systems (Singh & Banerjee, 2015); a flat horizontal angle for all systems (Hong et al., 2017); or a hybrid where panels on sloped rooftops are assumed to be parallel to the roof slope but those on flat roofs are assumed to be installed at an optimal fixed tilt for the region (Mainzer et al., 2014).

closely packed on rooftop and therefore do not account for space between panels. Finally, I calculate in GIS the estimated June 2008 solar PV output for each individual suitable rooftop area ($PVOutput_i$) using Equation 3.

Equation 3.

$$\text{PVOutput}_i\ (\text{kWh})=(\text{Wh}_i)*\left(\frac{\text{kWh}}{1000\text{Wh}}\right)*_{\eta PV}*_{\eta PR}$$

For solar PV cells, panel efficiency (ηPV) measures the ability to convert solar radiation into electrical energy (Yerli, Kaymak, İzgi, Öztopal, & Şahin, 2010) while the performance ratio (ηPR) accounts for system losses associated with inverter and transformer mismatch, wiring, DC to AC conversion, and soiling (Carl, 2014). In this study, I utilize a panel efficiency value of 14.5% and performance ratio of 71% based on a review of values reported in studies modeling rooftop PV technical potential (Table 8).

The ηPV I use for this analysis (14.5%) is the average efficiency reported by Mainzer et al. (2014) for polycrystalline silicon solar cells, which they note are the most common type of solar cells for rooftop solar installations. The same ηPV is also assumed by Singh & Banerjee (2015) who select the median conversion efficiency from a database of 12,622 commercially-available solar panels made of different materials and by different companies. In terms of ηPR, a number of studies cite ratios in the range of 75%-85% to account for the combined effects of soiling, module mismatch, wiring resistance, and DC to AC conversion (Carl, 2014; Castellanos et al., 2017; Hong et al., 2017; Singh & Banerjee, 2015). However, these estimates do not appear to take into account a temperature correction factor. Jakubiec and Reinhart (2013) suggest derating panel efficiency based on ambient temperature, given that increasing internal panel temperature adversely effects panel production. For crystalline modules, the temperature reduction factor recommended by the California Energy Commission for rooftop PV system design calculations is 89% (California Energy Commission, 2001). For this analysis, I calculate a performance ratio of 71% utilizing the soiling, module mismatch /wiring resistance, DC to AC conversion, and temperature correction values recommended by the California Energy Commission (2001). This is essentially equivalent to taking the midpoint performance ratio value from the range reported by other studies and multiplying it by the California Energy Commission recommended temperature correction factor (i.e. 80%*89% = 71.2%).

Based on these calculations, I find that the total technical solar PV potential for June 2008 across parcels for which I also have SMUD electricity consumption data is approximately 95 gigwatt hours (GWh) with a mean production of 6.84 kWh daily. Comparatively, the total June 2008 consumption across these parcels is approximately 816 GWh. Thus, the estimated production from suitable rooftop area in the City of Sacramento could supply approximately 12% of the observed consumption.

Table 8. Solar cell efficiency and performance ratio values reported in studies evaluating rooftop PV technical potential

Citation	Study Location	Solar Cell Efficiency (ηPV)	Performance Ratio (ηPR)
Hong et al. (2017)	Seoul, South Korea	Assume 15% (cite range of 15–18%)	
Carl (2014)	Kona, Hawaii		Cite range of 75% to 77% based on review of the literature
Castellanos et al. (2017)	Numerous	Assume 15%	Assume 75%
Mainzer et al. (2014)	Germany	Assume 14.5% for polycrystalline silicon	Assume 85% for polycrystalline silicon installations
Singh & Banerjee (2015)	Mumbai, India	Assume 14.5%	Assume 85%
Jakubiec & Reinhart (2013)	Cambridge, Mass	Assume 18.5%	
Nguyen & Pearce (2013)	Kingston, Ontario	Cite efficiencies over 10%	
Mustafa (2012)	Cairo, Egypt	Assume the following efficiencies: - Single-Crystalline Silicon at 15% - Polycrystalline Silicon at 14% - Thin-film Silicon at 9% - Thin-film Cadmium at 10%	Assume the following components in their performance ratio: -Temperature correction factor of 80% -Dirt and dust reduction factor of 93% -Module mismatch and wiring reduction factor of 95% -DC-to-AC conversion efficiency factor of 90% (cite range of 88-92%) -Stand alone system battery efficiency factor of 85%
California Energy Commission (2001)	California		Assume the following components of a performance ratio for crystalline modules: -Temperature correction factor of 89% -Dust correction factor of 93% -Wiring correction factor of 95% -AC conversion factor of 90%

In order to compare the estimated PV technical potential to the monthly meter-level consumption data obtained from SMUD, I apportion the technical potential to the meter locations associated with the SMUD electricity consumption dataset. While this effort may seem straightforward, it is complicated by the fact that in some cases the relationship between a meter location and a suitable rooftop area is not one-to-one but many-to-one (e.g. an apartment building); one-to-many (e.g. a parcel with one meter location but multiple buildings having suitable rooftop area); or many-to-many (e.g. an industrial site with multiple meters and multiple buildings with suitable PV rooftop area). Moreover, this meter-level apportionment is necessary given the fact that in certain locations different meters located within a single parcel are connected to different feeders. To apportion the technical potential to individual meter locations, I determine the number of meter location points in a parcel using ESRI's "Aggregate Points" tool; sum the total rooftop PV technical potential within a given parcel using ESRI's "Zonal Statistics as Table" tool; then divide the parcel-level technical potential by the number of points in the parcel; and, spatially join the resulting value back to the meter location points in that parcel. Finally, with both the consumption and estimated production per meter point, I merge meter points falling in the same location (e.g. in a multi-unit apartment building with individual meters for each unit). I sum the consumption and the PV technical potential of the merged points such that there is one point for each location representing the combined consumption and production of the merged points.

C. Network Construction

In order to evaluate the degree to which the modeled PV technical potential could offset the given electricity consumption throughout the networked SMUD grid system, I construct a topological network model of the SMUD electrical grid in ArcGIS using coded network connectivity data provided by SMUD. A network (graph) is a diagrammatic representation of a system that consists of nodes (vertices), which represent the entities of the system, and links (edges), which represent interconnection between those entities (Estrada, 2012). Figure 22 conceptually represents a portion of typical distribution feeder on the left and a network representation of the same portion on the left. Spatial networks contain nodes and links embedded in geometric space with constraints on topological characteristics including connectivity, adjacency, and incidence (Curtin, 2007; Halu, Scala, Khiyami, & González, 2016).

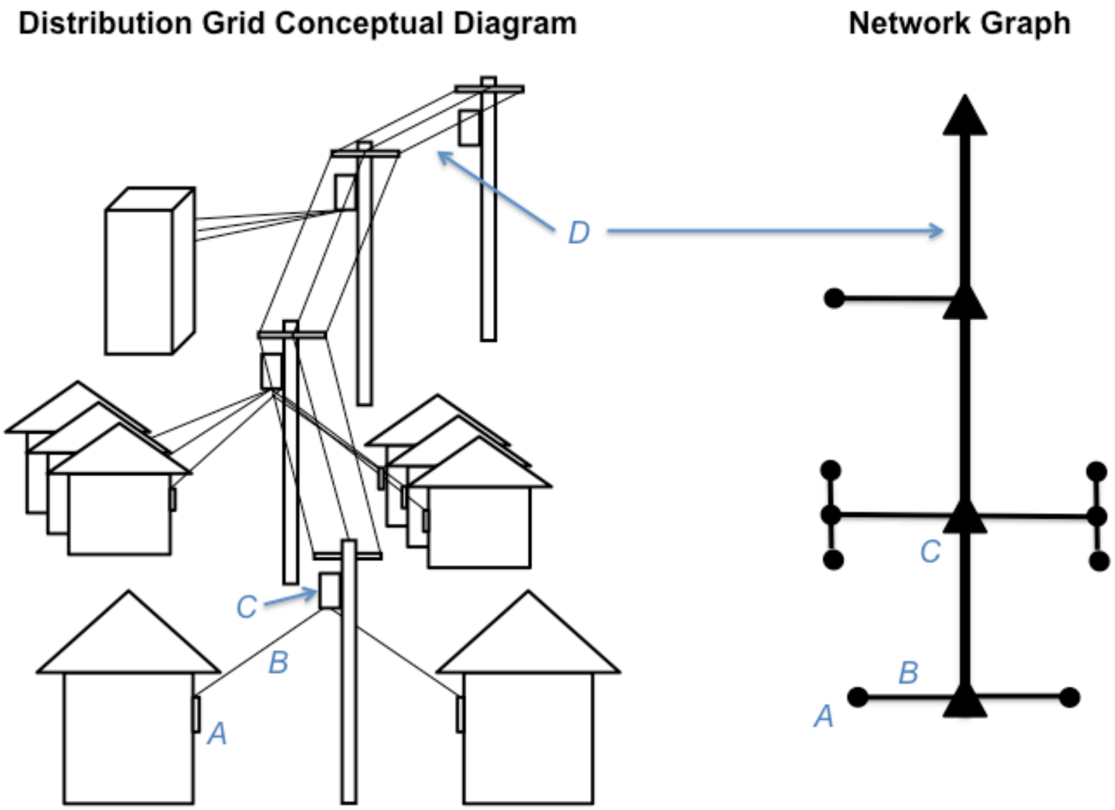

Figure 22. Distribution grid conceptual diagram and representative network graph. Distribution grid component A (left) represents the meter at the building level (and corresponding meter vertex on the right). Line B (left) represents the service drop from building meter to a transformer (and corresponding service drop edge on the right). Component C (left) represents the transformer (and corresponding transformer vertex on the right). Line D (left) represents the secondary distribution feeder line (and corresponding secondary distribution feeder edge on the right).

The SMUD dataset contains geo-located meter points and identifying codes for each meter's transformer, secondary feeder, primary (sub-transmission) substation, primary feeder, and transmission substation network connections. For each record in the dataset (i.e. each metered consumption point), SMUD provides the identifiers for its networked connections such that it is possible to generate a topological representation of the network from the meter points up to the transmission substations. Given that the SMUD dataset contains coded identifiers but no geographic information regarding the location of transformers, feeder lines, or substations, the network representation I generate is purely topological—accurately representing connectivity but not necessarily the real geographical location or length of elements in the electrical network. Like Halu et al. (2016), I generate a acyclic (tree) network topology of linear connections between electrical network nodes using a minimum spanning tree (MST) algorithm. The MST assumption is simplifying but realistic for an electrical network as the cost related to line lengths is often assumed to be the most dominant factor driving network topologies (Halu et al., 2016). Moreover, the network is non-planer allowing edges that cross but do not connect. Edges connect only at specified nodes.

Starting with point data representing the locations of the SMUD meters within the study region (see section II.A of this chapter), I generate an initial set of edges representing the MSTs between meter points that are connected to the same transformer (essentially service drops). I produce these MSTs using a python scripted Euclidian MST generating program built into an ArcGIS tool (D. Radke, 2016a). This tool computes the MST between a set of points using Prim's algorithm and allows the user to group sets of points using a specified attribute value (D. Radke, 2016b). I use this ArcGIS tool to initially generate MST graphs between metered consumption points that are connected to the same transformer (using transformer ID as the point grouping field). I then generate a centroid point within each MST to represent the transformer for that line using ESRI's "Add Geometry Attributes" tool. These transformer centroids, along with demand points that connect directly to the secondary feeder (those that have transformer IDs that are not shared with any other demand points), become the input points for another round of MST graphs with the secondary feeder ID as the point grouping field. I produce a centroid point within each secondary feeder MST and these centroids become the input points between which I generate MSTs with the distribution substation ID as the point-grouping field. I follow the same procedure to generate primary feeder and transmission substation MST edges. I conclude the network with centroid points that represent transmission substations on the transmission substation MST edges. To ensure the network is topologically connected in the correct manner, I use ESRI's topology toolset to validate connectivity between each set of edges and their associated nodes via snapping and topology rules (e.g. meter points must be covered by the set of edges that connect meter points sharing the same transformer). Figure 23 shows a representative portion of the topologic network I generate for this analysis delineated by interconnection levels. The top panel in the figure represents the meter points, service drop edges, transformer points, and feeder edges similar to what is conceptually shown in Figure 22. Figure 24 shows the whole topological network for the SMUD service area symbolized as a single feature to provide an idea of the extent of the network.

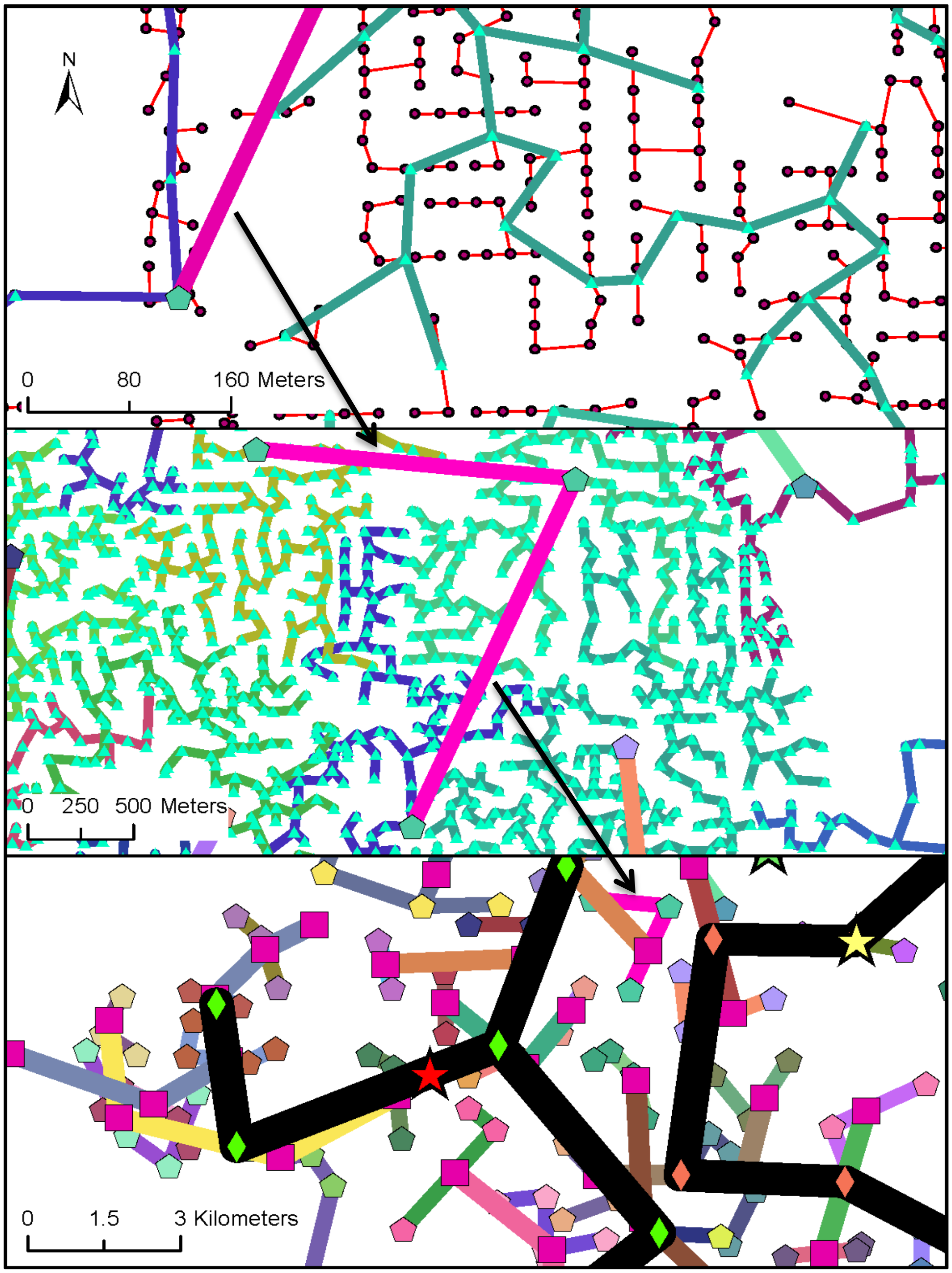

Figure 23. Topological network representation of the SMUD electrical grid. The top image represents the meter points through the secondary distribution feeders and the lines connecting secondary feeders to distribution substations. The middle image represents the secondary feeders and lines connecting them to distribution substations from a more zoomed out perspective. The bottom image represents two additional levels of connection from the distribution substations through primary feeders up to lines connecting primary feeders to the transmission substations (stars). The black arrows across images point to the same feature for reference purposes.

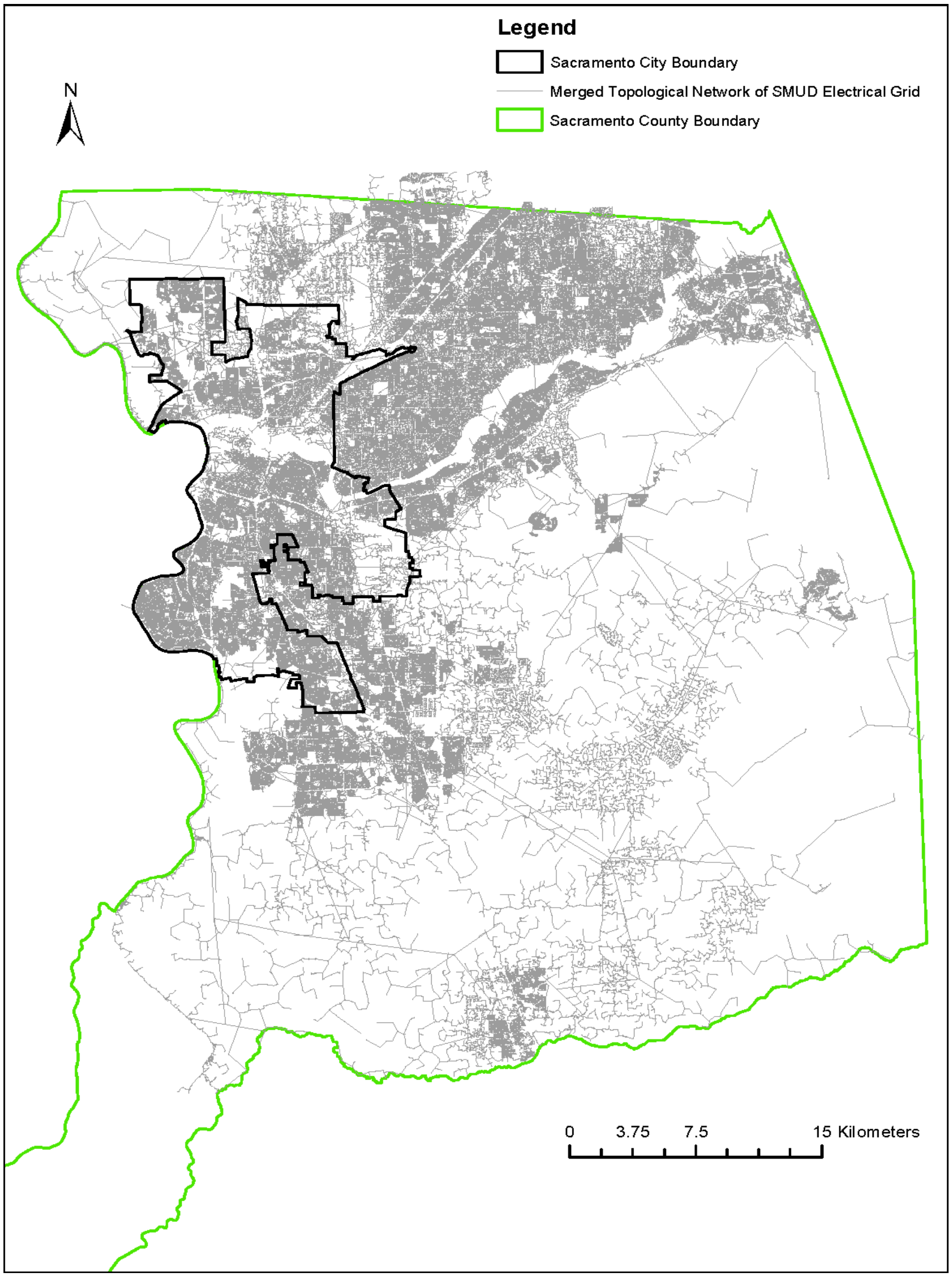

Figure 24. The full extent of the topological network representation of the SMUD electrical grid.

D. Quantifying the Balance of Electricity Supply and Demand within the Network

Given the recorded consumption and modeled potential PV production at each meter location, I quantify and spatially model in GIS the difference between electrical energy demand and supply across the entire network from the bottom-up, starting at the meter 1evel, through secondary and primary distribution feeders, all the way to the transmission substations. While numerous studies that quantify rooftop PV technical potential have suggested comparing the results to electricity demand as an avenue for future study, those that do have generally done so at high levels of aggregation—comparing total distributed generation to total estimated or known supply at a regional level—with little consideration for the locational relationship of supply and demand within a networked system (location-allocation). For example, Mainzer et al. (2014) suggest that connection of rooftop solar potential with building information about electricity consumption would allow for conclusions about possible self-consumption and the necessary distribution network, but that the high cost of creating such a model has hindered widespread application. Moreover, other studies comparing distributed renewable supply to demand often rely on estimates of consumption based on factors such as building characteristics, population distribution by building (Santos et al., 2014) or area, or regional consumer characteristics (Mainzer et al., 2014). In contrast, the approach I take herein focuses on the location-allocation of potential PV production relative to consumption within an entire regional networked system and relies, at its core, on actual measured consumption at the meter-level.

The potential for PV generation is not evenly distributed across feeders or at the same location on each feeder (URS, 2014), and there is considerable variation in energy use between neighborhoods within the same city (Kammen & Sunter, 2016). Therefore, analysis of the location and quantity of potential generation relative to the spatial distribution and magnitude of demand within a networked system is critical to determining where consumption could be satisfied by distributed PV production within the network. Despite this, few studies of potential distributed PV production have spatially analyzed supply and demand relationships within a network-modeling framework. Many studies recommend as future research comparison of distributed PV potential to electrical demand to determine the self-supply ratio (P. Gagnon et al., 2016; Hong et al., 2017; Kodysh et al., 2013); some studies draw broad comparisons of solar PV technical potential to estimated demand at a regional scale (Hofierka & Kaňuk, 2009; Kammen & Sunter, 2016; Mainzer et al., 2014; Singh & Banerjee, 2015); and other studies evaluate the self-supply ratio of buildings, clusters of buildings, or a neighborhood, but without considering associated existing network connections (Quan, Li, Augenbroe, Brown, & Yang, 2015; Santos et al., 2014). Nguyen and Pearce (2013) develop a methodology to determine PV generation potential by distribution feeder and apply it to an example feeder in Kingston, Ontario. However, their objective is to identify a general rule of thumb for how much rooftop area on a given feeder may be suitable for PV deployment; they do not evaluate demand on the feeder they analyze. One published study that does evaluate potential rooftop PV supply and measured demand in a network context is Halu et al. (2016). This study evaluates potential microgrid clusters of buildings, some with rooftop PV systems, in Cambridge, Massachusetts using power flow modeling and identifies optimal microgrid topologies for resilience and congestion mitigation. However, they identify generator nodes independently according to a 20% adoption rate, and only model residential buildings.

In this study, I quantify how much of the July 2008 consumption at each network level (i.e. meter, transformer, feeder, substation) could be offset by the estimated July 2008 rooftop PV technical potential to which it is connected in the network model (e.g. the net balance of electricity demand and supply or delta kWh [δkWh]). At the meter-level this involves simple subtraction of the kWh of PV technical potential associated with the node from its consumption. A negative δkWh value indicates that the modeled PV production is greater than the consumption associated with that meter. At the next network, level I use ESRI's "Spatial Join" capability to sum the δkWh values of all the meter points connected to the same transformer and transfer the summed attribute to the edge connecting the points. This gives the net δkWh balance across all the points connected to the same transformer. I then use Spatial Join again to transfer the δkWh from the edge connecting these meter points together to the centroid of that edge (representing the transformer). I follow the same procedure to sum the δkWh of all transformer points connected to the same secondary distribution feeder and transfer the result to the edges and then centroid of that secondary feeder. A negative δkWh for a secondary feeder suggests that the PV supply across all the points connected to that feeder is greater than the demand across those points. I repeat this procedure to summarize the δkWh at all secondary feeder centroids connected to the same distribution substation and transfer that value to the edges connecting secondary feeder points and then the centroids of those edges, which represent the distribution substation. I continue this process up to the transmission substations. Using this approach, I spatially demonstrate across the network the magnitude of self-supply and highlight network locations where there is more estimated PV production than consumption (i.e where δkWh is negative).

It is important to note that the balance of supply and demand on network elements (edges and nodes) can also be evaluated using the geometric network data model in ESRI's ArcGIS. The geometric network data model allows the user to establish inter-connectivity rules among the various sets of edge and junction (node) types (e.g. an edge of type A may connect to an edge of type B through the set of junctions of type C). The user can then use ESRI's geometric network analysis tools to trace the network to find and select all interconnected elements up or downstream of a point and summarize attribute values across the selected elements. I explore this methodology for this analysis, however, the trace method requires identifying a point to measure up or downstream from for each trace and would have been a prohibitively time consuming approach to determine the balance of supply and demand at each element in the network as accomplished in the spatial join approach I use herein. By manually defining what element attributes are summarized and spatially joined to other topologically connected attributes, I essentially manually enforce edge-junction-edge connectivity rules as would occur in a trace using a geometric network data model. The spatial join method allows me to accomplish these calculations for every element (nodes and edges) all the way from the meters to the feeders up to the transmission substations across the entire network in a relatively short amount of time while still imposing edge-junction-edge connectivity.

The results of this analysis are presented in Section III below.

E. Future Urban Development Modeling

In the final step of this approach, I simulate the potential future urban development under a rooftop PV build-out scenario and a base scenario for the City of Sacramento. Comparing how land use under these scenarios differs provides insight into how changes in the supply and net demand along the electrical grid due to build out of the suitable distributed rooftop PV generation might shift development patterns. I model future urban growth patterns using the simple, rule-based model UPLAN.

There is a vast body of literature on urban growth and land use development modeling, a variety of types of urban growth models, and numerous individual models.[47] It is outside the scope of this paper to summarize in detail the history, theory, and state of urban growth modeling. Silva & Wu (2012), Musa, Hashim, & Reba (2017), and van Schrojenstein Lantman, Verburg, Bregt, & Geertman (2011) provide an excellent starting point for such a summary. In general, cities are characterized by complex patterns of land use that are shaped by change and growth as individuals and public and private corporations act simultaneously in time over the urban space (Barredo, Kasanko, McCormick, & Lavalle, 2003). Urban growth models attempt to predict these patterns by simulating the influences that underlie these actions. The basis for these models is Tobler's first law of geography that "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970, p. 236). Modeling approaches have evolved over time from traditional linear and mathematical approaches to include more complex, dynamic, and intelligent elements, often in GIS environments, and as the variety of models has grown so have the number of schemes to classify model types (Musa et al., 2017; Silva & Wu, 2012). Most classification systems focus on modeling approaches and describe cellular automata, agent-based models, and fractals as the primary urban growth modeling techniques (Batty, 2007). Silva and Wu (2012) review 64 urban models currently used in practice and classify them according to six benchmarks: (1) modeling approaches, (2) levels of analysis, (3) spatial scales, (4) temporal scales, (5) spatial and aspatial dimensions, and (6) different planning tasks. The primary modeling approaches they classify models into include: mathematical/statistical models, GIS-based models, cellular automata models, agent-based models, rule-based models, and integrated models.

E.1 The UPLAN Model

The UPLAN model[48] used in this analysis to simulate future urban growth is classified by Silva & Wu (2012) as a rule-based, urban-growth focused, multiscale, spatial model that simulates urban development in a GIS environment based on user-defined landscape feature attractiveness, growth constraints, and demographic characteristics. The model is designed to be a bottom-up, supply-side, scenario-testing model that can be applied to any metropolitan region (R. A. Johnston & Gao, 2002). It is deterministic (rule-based) and therefore does not require calibration with historical data and does not use choice or other statistical models (R. A. Johnston & Gao, 2002). According to W. T. Walker, Gao, and Johnston (2007), UPLAN should be thought of as approximating a synthetic land use market that simulates developer decisions given land use plans, policies, and development attractiveness related to relevant natural and built features defined by the user.

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[47] Urban growth models are sometimes distinguished from land use models in the literature and in other cases the two terms are used synonymously. In this case, I use the term "urban growth models" to refer to both types of models.

[48] The UPLAN model was developed and is maintained by the Information Center for the Environment at the University of California, Davis. The original version of the model was developed around the year 2000 (R. A. Johnston & Gao, 2002) and operated with raster-based inputs and outputs. Two subsequent raster-based versions were released followed by the current fourth version of the model that was released in 2017 and is the first version to operate with only vector-based spatial data (Boynton & Thorne, 2016). The model is described in detail in published papers and user manuals (Boynton & Thorne, 2016; B. Johnston, Lehmer, Gao, Roth, & McCoy, 2007; R. A. Johnston & Gao, 2002; W. T. Walker, Gao, & Johnston, 2007).

The UPLAN model relies on vector data that represent minimum mapping units, existing urban development, local general land use plans, and other relevant natural and built features, in order to project the spatial allocation of residential and employment growth via assignment of user-defined land use categories (Boynton & Thorne, 2016). The primary assumptions driving the model are that population growth can be converted into demand for land use by applying conversion factors to employment and households; new urban expansion will conform to city and county general plans; locations have different attraction weights because of spatial relationships to attractors and detractors; and, some areas (e.g. lakes) will exclude development and others (e.g. floodplains) will constrain development (Boynton & Thorne, 2016). The model endogenously converts input population projections for the region into the acres needed for future employment and housing based on user-specified factors including persons and employees per household; acres per household; industry floor area ratios (FARs) and average square foot per employee in various land use categories; and what percentage of the total future employees or residents go into each land use category (W. T. Walker et al., 2007). These calculations produce a table of land demanded for each land use category, from which the model operates its land allocation routine. The general plan layer defines where these different land use categories can be developed based on user-defined specifications for the general plan land use classes (Boynton & Thorne, 2016). The model then generates a composite suitability attraction layer based on the attractor and detractor distance weights specified by the user as well as any constraints. Finally, demand for each land use category is allocated to the minimum mapping units starting with the unit with the highest composite attractiveness score for that land use category. The results of this allocation process are the output of the model and include the locations and acres per location allocated to each land use category.

E.2 City of Sacramento 2035 Urban Growth Scenario Modeling

For the two future scenarios simulated in this study, I model urban growth out to 2035 using model input data I obtain primarily from the City of Sacramento's 2035 General Plan (City of Sacramento, 2015) and U.S. Census Bureau (2018) data. I determine the population increase expected by 2035 to be 139,500 people based on the city's population of 500,900 in July 2017 (U.S. Census Bureau, 2018) and expected growth to approximately 640,400 by 2035 per the city's General Plan (City of Sacramento, 2015). Based on U.S. Census Bureau (2018) figures, the city averages 2.65 persons and 1.57 employees per household. I use the existing parcels in the city as the minimum mapping unit for the scenarios (Figure 25) and prescribe six land use categories to be allocated by the model including high, medium, and low density residential categories, and commercial, industrial, and retail employment categories.

I determine the other input demographic factors required by the model (residential acres/unit; square feet per employee; FAR) from the city's General Plan housing and community development elements (City of Sacramento, 2015) as well as current city demographics (City of Sacramento, 2018a). A layer delineating the city's 2035 General Plan land use classes serves as the general plan layer (Figure 26) defining where the six different land use categories can be developed based on my specifications cross walking the UPLAN land use categories with the General Plan's land use classes. The parameter values I input for all of these variables remain consistent across both of the future scenarios I run through the model.

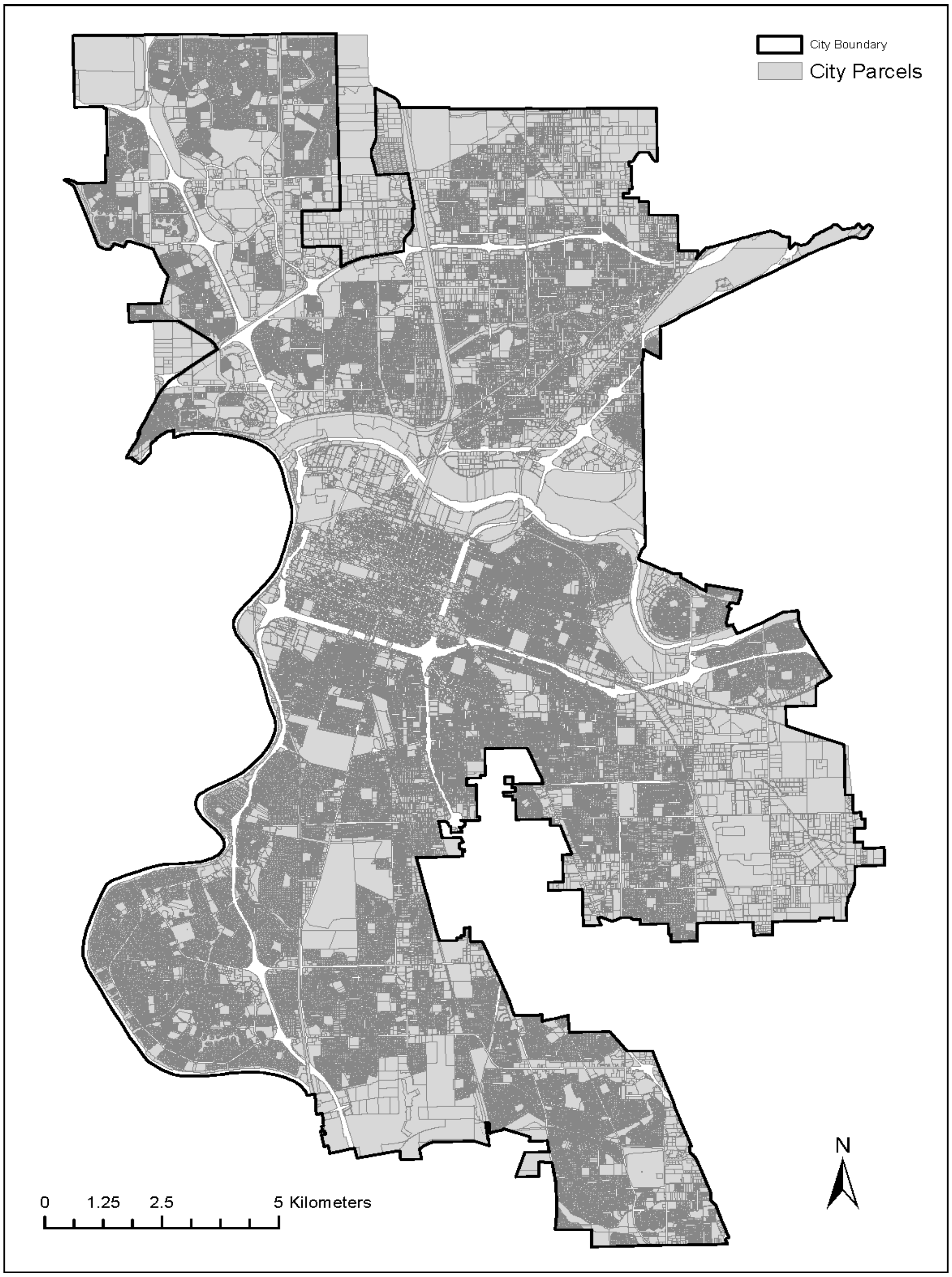

Figure 25. Sacramento City parcels used as the minimum mapping unit for the UPLAN urban growth modeling scenarios.

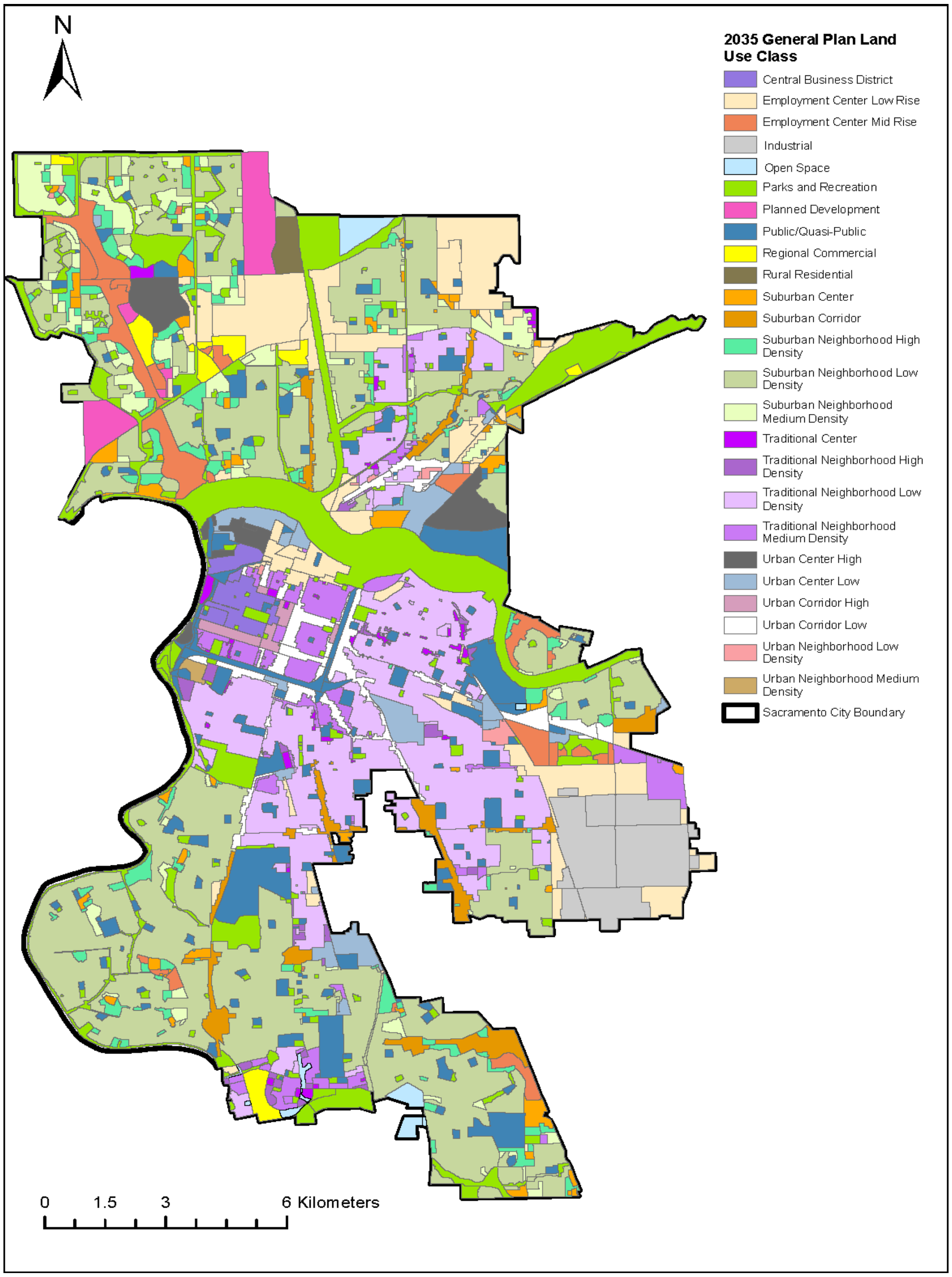

Figure 26. Sacramento City 2035 General Plan land use classes. This data serves as the general plan layer for the UPLAN urban growth modeling scenarios.

I use the same attractor, detractor, and constraint layers and weights for each land use category across both scenarios, except for two additional attractors, which are specific to the rooftop PV build-out scenario. Figure 27 and Table 9 illustrate and describe the geospatial data layers I use for attractors, detractors, and constraints across these scenarios.

As described in Boynton and Thorne (2016), for each of the six land use categories I specified for allocation by the model, I select which attractors or detractors influence the land use and set weighted distances ("weight points") to govern the strength of the influence. The UPLAN model interpolates weights linearly between weight points to assign weight values to minimum mapping units based upon their distance from the feature. I add an additional attractor layer for the PV build-out scenario that represents the electrical network lines with surplus PV supply assuming an increased attractiveness for development in areas where new energy consumption can be optimally sited because there is surplus local supply. I also add a second additional attractor layer representing areas of higher than average insolation based on the assumption that future development will seek to integrate distributed rooftop PV, and thus, areas with greater solar resource would be more desirable than those without, all else being equal. Figure 27 (right) illustrates these two attractors specific to the PV build-out scenario. For constraint layers, I specify (as a percentage) how much available space for development will be reduced if a minimum mapping unit intersects the constraint. Because the objective of this scenario exercise is to observe how distributed rooftop PV build out may shift future growth patterns, and not necessarily to accurately model where growth might realistically take place, I do not use existing urban development as a constraint to future development.

The results of the urban growth modeling are presented and discussed in the following section.

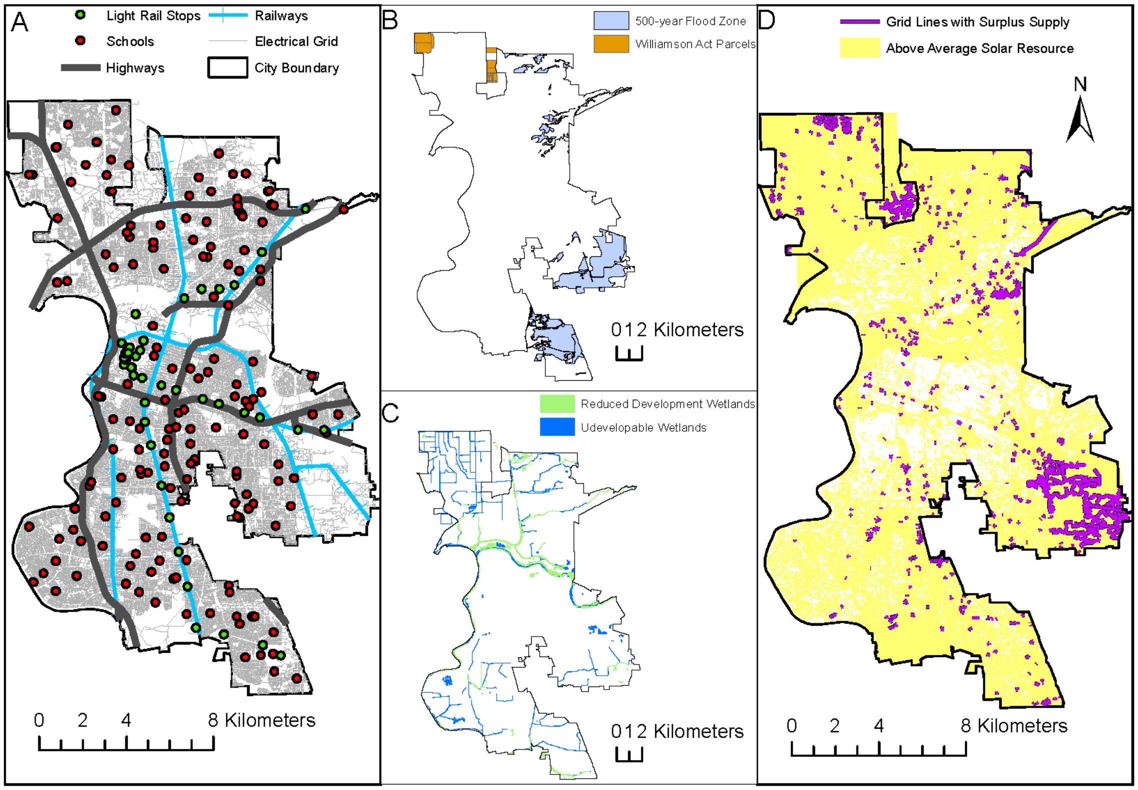

Figure 27. Geospatial data inputs for UPLAN urban growth modeling scenarios. Image A (left) shows attractors common to both scenarios, image B (middle top) shows detractors common to both scenarios, image C (middle bottom) shows constraints common to both scenarios, and image D (right) shows the additional attractors added in the PV build out scenario.

Table 9. Data layers used in UPLAN urban growth scenarios

		Scenario Including the Layer		
Layer	**UPLAN Type**	**Base**	**PV Build Out**	**Notes**
Sacramento City Parcels[1]	Minimum Mapping Units	X	X	
Sacramento 2035 General Plan Land Use Classes[3]	General Plan	X	X	
Highways[2]	Attractor	X	X	
Light Rail Stops[2]	Attractor	X	X	
Railways [2]	Attractor	X	X	
Schools[3]	Attractor	X	X	
Electrical Network (All Lines)	Attractor	X	X	All edges in topological network model
Electrical Network (Surplus PV Supply Lines Only)	Attractor		X	Only edges from topological network model that have surplus supply
Solar Insolation Above Mean	Attractor		X	June 2008 monthly insolation resampled to $30m^2$ cells; selected only cells above mean insolation for the region then converted to polygon
500 Year Flood Zone[4]	Detractor	X	X	
Williamson Act Parcels[2]	Detractor	X	X	Restricted use other than for agriculture
Wetlands[5] (Full Exclusion)	Constraint	X	X	Lakes, rivers, ponds
Wetlands[5] (Reduce Development)	Constraint	X	X	Emergent, forest/shrub wetlands

Data Sources: [1] Sacramento County GIS (2016); [2] Sacramento County GIS (2018); [3] City of Sacramento (2018b); [4] Federal Emergency Management Agency (2016); [5] U.S. Fish and Wildlife Service (2018)

III. Results

The results of this analysis show that the magnitude of potential PV generation relative to the magnitude of demand varies across the topological network model I use to represent the SMUD electrical system[49] both spatially and in terms of network scales (e.g. at the meter vs. feeder level). Importantly, I identify areas in the City of Sacramento where the June 2008 PV technical potential exceeds the actual June 2008 consumption suggesting surplus supply occurs along portions of the grid and is only balanced out by local consumption captured at greater network scales. Results include quantification of the magnitude of offset demand or excess supply for

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[49] It should be noted that while I generate a topological network model and include consumption data for the entire SMUD electrical network, which covers a large portion of Sacramento County, I only model rooftop PV technical potential production in and immediately adjacent to the City of Sacramento boundary. Thus, I focus this discussion of results solely on the Sacramento City region.

network elements from the meter-level to the transmission substation. Using the results of the network modeling in a subsequent urban growth analysis, I find that relative to the base growth scenario, the distributed rooftop PV build-out scenario has both locally concentrating and regionally dispersing influences over future urban growth patterns. Furthermore, I find that the amount of certain land uses allocated under these scenarios differs.

A. Network Energy Supply-Demand Balance Results

The net balance of electricity demand and supply (δkWh) across the SMUD electrical network in the City of Sacramento for the month of June 2008 is generally illustrated in Figure 28. Edges and nodes in blue represent network locations where the estimated monthly PV production from identified suitable rooftop area is greater than the monthly consumption at the node or along the edge element. Conversely, edges and nodes in red represent areas where the monthly consumption is greater than the estimated PV production at the node or along the edge element. Figure 28A illustrates the δkWh at the secondary distribution feeder level (i.e. feeders connecting groups of distribution transformers) and suggests that secondary feeders at the north (1), northeast (2), and southeast (3) edges of the city have greater estimated PV production than electricity consumption.

Area 1 (as labeled in Figure 28A) has some hotspots of high June 2008 consumption per square mile (Figure 17) but is a low-rise commercial region with large buildings that provide vast suitable rooftop area and large estimated PV technical potential that appears to exceed demand. Areas 2 and 3 have relatively low June 2008 consumption per square mile as illustrated in Figure 17. The vicinity of Area 2 has low- and medium-density residential and low-rise commercial land uses, which provide enough suitable rooftop area and estimated PV technical potential to exceed demand. Area 3 is an industrial region with large warehouses that, similar to Area 1, provides vast suitable rooftop area and large estimated PV technical potential to offset an already relatively low demand. Figure 28C illustrates the secondary distribution feeders in a portion of Area 3 (generally represented by the black box in Figure 28A) at a higher resolution and with individual meter (circle) and transformer (triangle) nodes included to demonstrate that even with some of these nodes having greater consumption than estimated production, the overall secondary distribution feeder has a net surplus of estimated rooftop PV supply. In particular, the fact that Area 3 has a surplus of supply is considerable given that the distribution feeder extends well beyond the city boundary and connects to additional consumption points for which I do incorporate SMUD consumption data into the net demand-supply balance on the feeder, but for which I did not attempt to model suitable rooftop area so they contribute no additional PV technical potential.

While the network elements up through the secondary distribution feeders (represented in Figure 28A and C) do show surplus estimated PV technical potential in a variety of cases, this is rarely true for network elements beyond the secondary distribution feeders. Figure 28B shows the net balance of production and consumption for the edges connecting the secondary feeder centroids to distribution substations, those connecting distribution substations (primary feeders), and those connecting primary feeder centroids to transmission substations (stars). Figure 28D shows a higher resolution view of the area in the black box in Figure 28B with the secondary feeder edges and centroids (squares), edges connecting secondary feeder centroids and the distribution substation centroids of those edges (circles), primary feeder edges connecting distribution substations and the primary feeder centroids (hexagons), and then the edges connecting primary feeder centroids to transmission substations (stars). Across the entire region, these figures show only one edge connecting two secondary distribution feeder centroids to a distribution substation that has surplus supply (Figure 28D). This edge is in Area 3. Similarly, there is only one transmission substation in the region that is modeled as having surplus supply, and it is connected directly to a distribution feeder in Area 3 (Figure 28D).

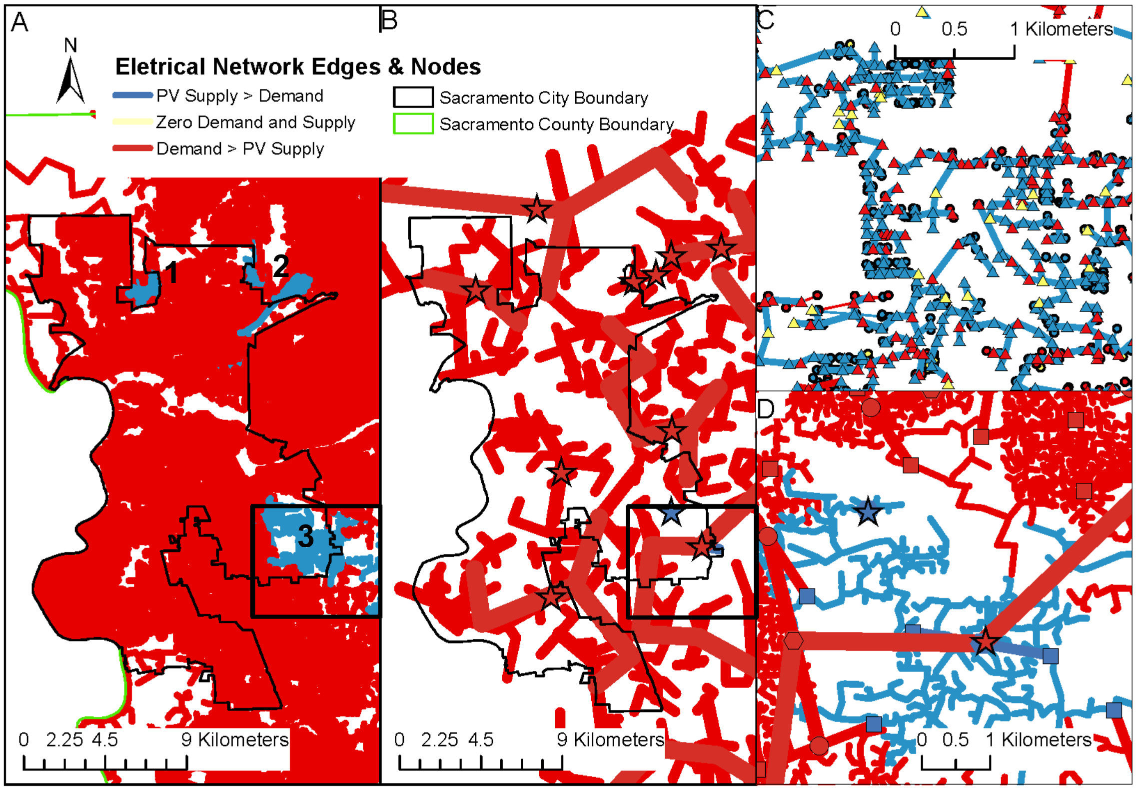

Figure 28. Net balance of electricity consumption and supply (δkWh) across the SMUD electrical network in the City of Sacramento for the month of June 2008.

The approach to modeling the net balance of electricity demand and supply across the SMUD electrical network presented here not only allows general analysis of where potential distributed energy generation may exceed consumption, it facilitates quantification of the offset demand or surplus supply for each element of the electrical network. In Figure 29, I illustrate the δkWh for the month of June 2008 along secondary distribution feeder edges (and transformer nodes in the inset) for a small portion of the SMUD network. Blue lines and nodes denote network elements with surplus supply, while red lines and nodes denote elements with offset demand. Yellow nodes in the inset represent nodes with no associated demand or supply. The magnitude of the surplus or offset is represented by the thickness of the corresponding edge or size of the corresponding node. This figure illustrates that even along network elements where full self-supply may not be achieved, the demand offset along the feeder could be substantial. Moreover, for network elements with excess supply, the type of information presented here can elucidate elements that may be providing the majority of the supply, such as the two transformer points represented by large blue triangles in the gray circle in the inset map. Using this approach, the same type of information can be obtained for each network element from the meter-level all the way up to the transmission substation.

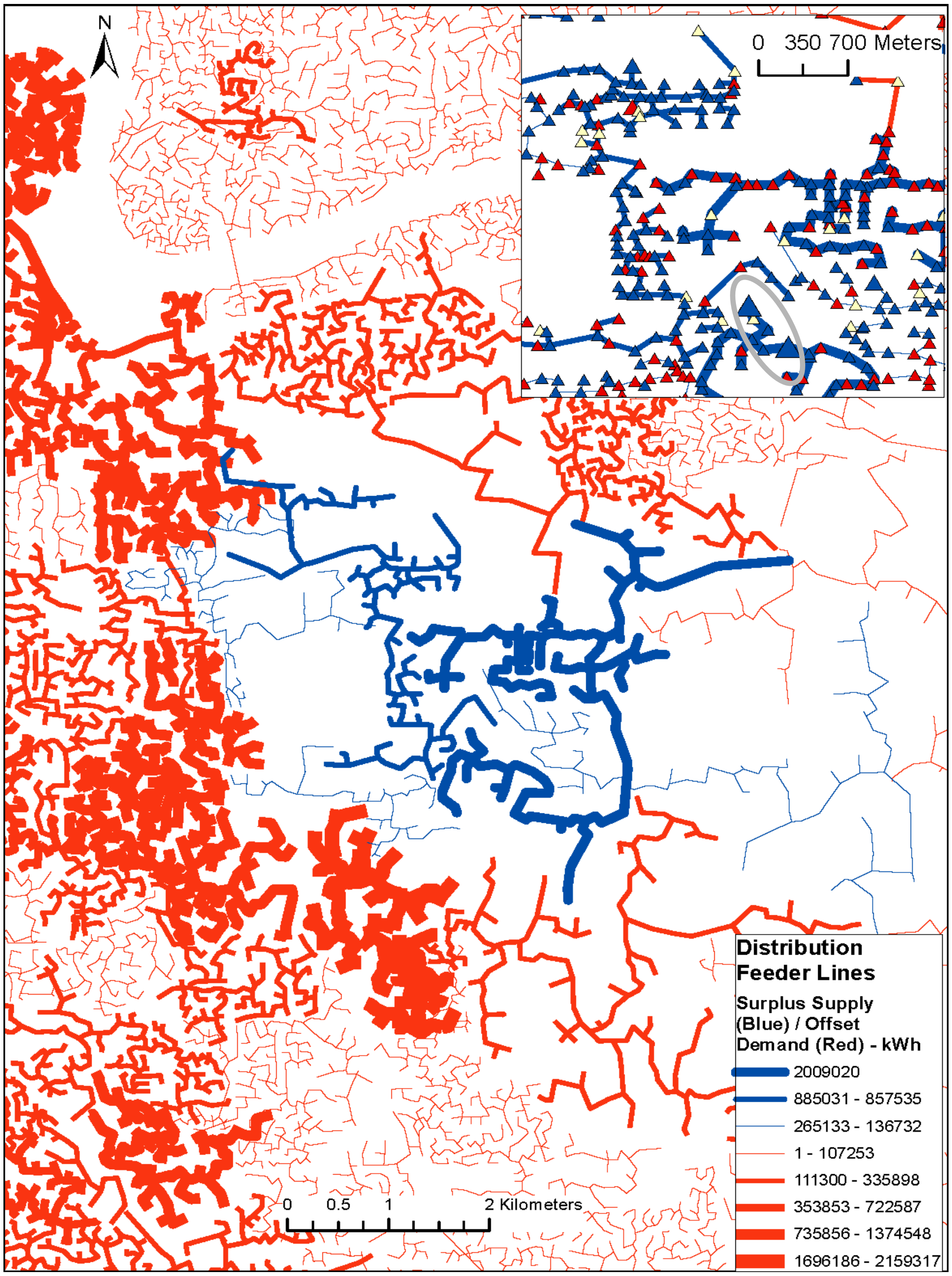

Figure 29. Net consumption-supply balance for June 2008 along secondary distribution feeder edges (main figure) and including transformer nodes (inset). Blue lines/nodes represent network elements with surplus supply and red lines/nodes represent those with offset demand. Yellow nodes represent zero demand and supply. The greater the magnitude of the surplus or offset, the thicker the edge or larger the node.

B. Sacramento Urban Growth Scenario Modeling Results

Based on the outputs of the urban growth modeling for the base and distributed rooftop PV build-out scenarios from UPLAN, I find that both scenarios accomplish full allocation of the projected additional population the City of Sacramento expects to support by 2035, but there are noticeable differences in both the patterns of future development and the amount of certain land use types allocated. The spatial allocation of the specified residential and employment land uses for the base (left) and PV build-out (right) scenarios are shown in Figure 30 and the acreage of each land use allocated in the scenarios is presented in Table 10. As described in section II.E of this chapter, the inputs to the two scenarios are identical except that the distributed rooftop PV build-out scenario assumes areas in proximity to network edges with excess distributed PV supply and areas with higher than average insolation are more attractive to development than those without these characteristics.

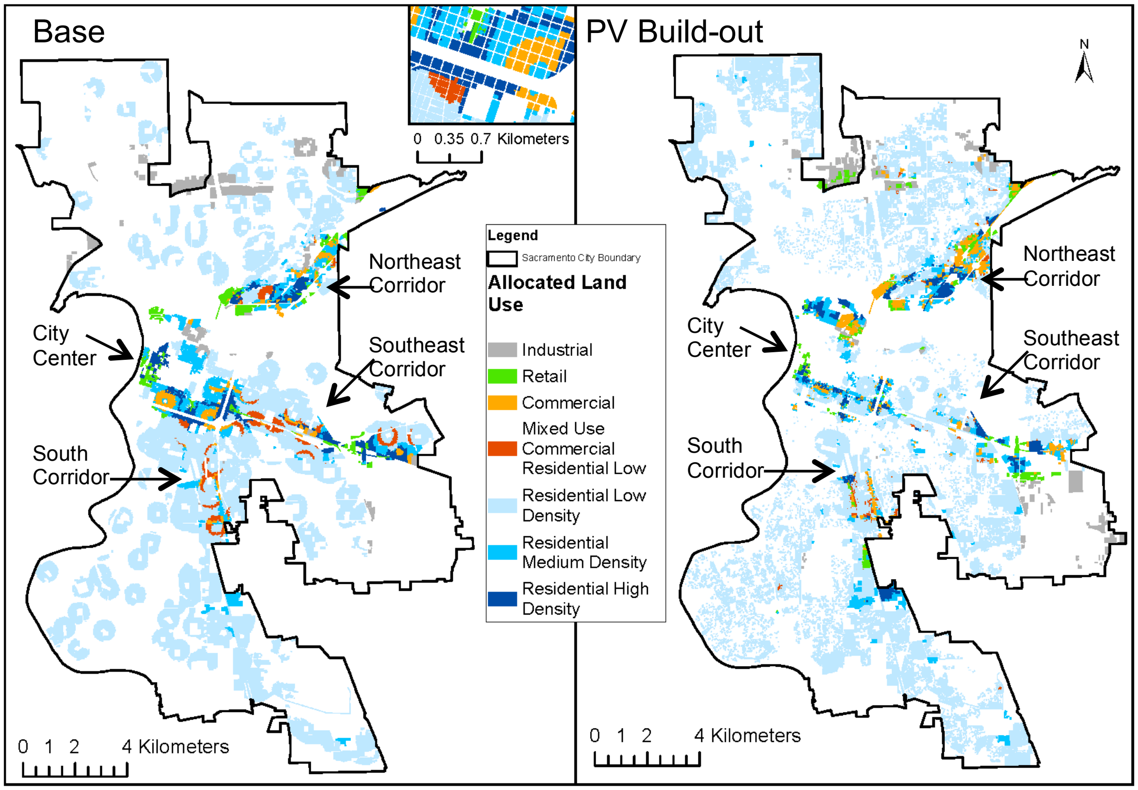

Figure 30. Spatial allocation of the specified residential and employment land uses for the base (left) and PV build-out (right) scenarios.

While the two scenarios allocate the same acreage of industrial, retail, and medium- and high-density residential land use (Table 10), the location of these future land uses differs between the two scenarios. Under the base scenario future land use development is concentrated in the city center (middle of the city towards the west) and along transportation corridors extending diagonally from the city center towards the northeast and southeast. This is consistent with the fact that highways, light rail stops, and railways all serve as attractors in the model and generally run along the transportation corridor diagonals. In contrast, under the PV build-out scenario, land use is less concentrated in the city center and along the southeast transportation corridor diagonal and more concentrated just north of the city center and along the northeast transportation corridor. Given the additional attractors under the PV build-out scenario, this result is intuitive because there is a concentration of network edges with surplus supply running along the northeast transportation corridor making this area more attractive for development. For example, while retail land use is allocated to the city center under the base scenario, in the PV build-out scenario, retail land use is instead allocated at the east end of the southeast transportation corridor and at the north center boundary of the city. Both these locations also have greater industrial land use than observed under the base scenario. The concentration of future development in these areas under the PV build-out scenario again seems driven by the location of network edges with excess supply presumably making development more locally attractive in these zones. Medium- and high-density residential land uses follow similar patterns between the two scenarios. Interestingly, at the southeast edge of the city, the detraction associated with the 500-year floodplain zone occurring in the area seems to be partially balanced by the attractiveness of network edges with excess supply and higher-than-average solar insolation in the same area, resulting in additional development in this location under the PV build-out scenario as compared to the base scenario.

Table 10. Acres of each land use type allocated in the base and PV build-out scenarios

	Industrial	Retail	Commercial	Mixed Use Commercial /Residential (Low)	Residential (Low)	Residential (Med)	Residential (High)
Base	904.2	392.4	373.3	823.3	9797.2	1081.1	601.5
PV Build Out	904.2	392.4	674.1	221.6	10098.2	1081.1	601.5

Also noticeably different between the two scenarios are the amount and pattern of low-density residential land use development. Under the base scenario, the model allocates approximately 9,800 acres to low-density residential development (Table 10) in a more concentrated pattern. In this scenario, low-density residential development is focused just outside the employment and higher-density residential land uses in the city center. Beyond that, additional low-density residential land use is concentrated around a light rail transportation corridor running directly south from the city center and in discernable round buffers associated with school locations (attractors) throughout the city region. In contrast, under the rooftop PV build-out scenario, there is a greater amount of low-density residential land use (approximately 300 acres more than under the base scenario; Table 10), and it is allocated in a much more diffuse pattern. Much less low-density residential land use is located immediately around the city center, and it is not discernably concentrated around schools under this scenario. Instead, low-density residential land use is much more diffusely distributed throughout the entire region. This can be attributed to the inclusion of the above average solar insolation attraction layer in the PV build-out scenario which lends greater attraction value to more land area throughout the city region, and thus, encourages diffusion of land uses. In comparison with the base scenario, there is also more low-density residential land use at the northern and southern boundaries of the city, which likely results from a combination of the above average solar resource and network edges with excess supply both increasing the attractiveness of these zones.

The increased attractiveness of land throughout the region under the PV build-out scenario due to the inclusion of the above average solar resource attraction layer also indirectly drives an overall reduction in allocation of mixed land use. The base scenario includes approximately 600 acres more mixed-use commercial with low-density residential than the PV build-out scenario (Table 10). In the base scenario, this mixed-use development is located along the city's three transportation corridors. Conversely, the PV build-out scenario has almost no mixed-use commercial with low-density residential land use anywhere throughout the region. Along with the 300 additional acres of single use, low-density residential development associated with the PV build-out scenario, it includes 300 additional acres of single use, commercial development as well. Thus, the low-density residential and commercial land use allocated as mixed development under the base scenario is, in contrast, allocated as separate single use commercial and low-density residential land use under the PV build-out scenario. This can be attributed largely to the fact that the above average solar resource attraction layer adds weight to the attractiveness of areas zoned for low-density suburban neighborhoods and corridors as (or more) attractive than those around the city center and transportation corridors which are zoned for urban center mixed uses (see zoning in Figure 26).

These results are noteworthy especially in the context of other potential urban sustainability goals. Greater density and compactness are often cited as relevant criteria for sustainable urban development (Lehmann, 2016). For example, in California, state laws such as SB 375 encourage compact transit oriented development to reduce carbon emissions from the transportation sector. However, the results of this analysis demonstrate the objective of integrating high levels of rooftop solar PV may conflict with the objective of encouraging greater urban compactness, because polices mandating distributed rooftop PV integration could encourage more diffuse urban development to take advantage of solar resource and thereby, result in less mixing of land uses. On the other hand, while increased urban density may be sustainable in terms of reducing transportation energy use, the resulting increased density of electricity demand may not be feasibly met by distributed renewable energy (Kammen & Sunter, 2016; Ko, Jang, Radke, & Cervero, 2013). Given this, theoretical and practical questions of scale in energy provision and urban planning remain (Kammen & Sunter, 2016).

IV. Discussion and Conclusion

Urban areas are recognized as being at the crux of achieving a more sustainable energy future given their role as large consumers of energy and their potential to site large quantities of distributed renewable generation close to consumption. At the same time, change in the technologies, scale, and locations from which electricity is supplied can be expected to impose unique influences on urban spatial structure and affect future patterns of urban development (Amado & Poggi, 2014; Kirby Calvert & Simandan, 2010; Owens, 1979, 1986). Yet, there has been limited research on the future urban and regional development implications of a transition to distributed renewable energy. To address this gap, I present an approach to 1) quantify the effect of shifts in the location of electricity generation on net demand along various elements of the electrical network, and 2) simulate the resulting influence of these network changes on patterns of future urban development. Using a case study of rooftop PV deployment in Sacramento, California, I analyze the network from the bottom up, and show that network elements from the meter-level through certain distribution feeders can exhibit PV technical potential that exceeds consumption. Furthermore, I demonstrate that relative to a base growth scenario, a scenario emphasizing distributed rooftop PV integration could have both locally concentrating and regionally-dispersing influences over future urban growth patterns, potentially decreasing mixed land uses in favor of diffuse single land use development. These results suggest that there is a potential for distributed renewable energy goals and policies to conflict with other objectives of sustainable urban development such as increasing mixed land use and urban concentration. Therefore, it is critical for policymakers and planners to employ models, such as the approach presented herein, in order to assess the complex interactions of sustainable urban development and energy policies and their effects on future urban growth.

With cities consuming approximately 75% of power generated globally and city-integrated renewable energy generation increasingly viewed as a feasible method to reduce urban carbon emissions (Kammen & Sunter, 2016), the effects of rooftop solar PV integration on the net balance of electricity supply and demand across the electrical grid, along with the influence of such network changes on patterns of future urban development, are of growing importance to policymakers and planners. Nguyen and Pearce (2013) call for participatory and multi-disciplinary urban energy planning and Santos et al. (2014) suggest that such efforts should support the formulation of policies for urban planning both with respect to promoting urban design optimized for renewable energy deployment and to guide urban regeneration and development. However, Amado et al. (2017) caution that planners and researchers lack defined methodologies to inform integrated energy and urban planning decision making. The approach presented herein is a critical step towards meeting this need.

Moreover, the specific results from my application of this methodology to the Sacramento region suggest that policymakers and planners seeking to balance sustainable future urban development objectives (such as increasing urban density and mixing of uses), while also increasing city integrated renewable energy may need to consider additional policies to do so successfully. For example, Amado et al. (2017) propose energy zones that seek to optimize land uses to balance the quantity and timing of renewable energy supply and consumption. In the Sacramento case, this is somewhat akin to utilizing the network elements with excess PV technical potential supply as attractors for development. The presumption is that infilling additional development in these locations as opposed to others will increase consumption and better balance out the available supply. Energy FITs based on net electricity demand/supply balance could also be used to selectively encourage PV integration where there is additional demand to be offset. Such tariffs could help to overcome the diffusion of land use associated with the assumption that all areas with above average solar resources will become more attractive to development as cities require integrated rooftop PV systems on all new housing, such as California has done with its recent change to its building codes in 2018. Instead, areas with FITs would be more attractive.

The methodology employed here is a particularly adaptable approach given its network, geographic, and temporal scalability. It is not tied to scale, distance, direction or density so the approach is universal. The results of the net demand supply balance can be readily summarized at different network element scales from the meter, to the feeder, to the substation, to the entire utility network. Similarly, while the analysis I present focuses on evaluating the net demand and supply balance over a full month, the method can be easily adapted to evaluate conditions at other temporal scales including hourly, daily, seasonally, or yearly. This is important because cities differ in both their energy needs and their available energy resources (Kammen & Sunter, 2016). The month of June approximates both peak demand and peak incoming solar radiation for the Sacramento region, but other times or scenarios may be of more interest in different regions. The urban growth modeling can also be adapted to include multiple time steps (e.g. modeling 2035 and 2050 growth) with different parameters. Geographically, I focus my analysis on

Sacramento, but this method can be used in any location where the necessary input demand, supply, and network data can be obtained or approximated. Given the adaptability of this approach, it offers a starting point for policy, planning, and implementation decisions at many levels.

Beyond the specific objective of understanding how distributed renewable energy integration may affect the electrical grid and influence patterns of future urban development, the information produced using this methodology has broad applications. The simulation of future urban development scenarios associated with transitions in our energy supply infrastructure is highly relevant to environmental planners in terms of evaluating the potential environmental effects of such future urban development on other natural resources. The methodology can be used produce accurate PV technical potential estimates at the building-level for large regions relatively quickly using LiDAR. The net balance of demand and supply across network elements itself can be used for the purpose of streamlining renewable energy interconnection assessments at high resolutions along the electrical network (Nguyen & Pearce, 2013). Additionally, combining such information with socioeconomic data could facilitate means of encouraging social equity of access to distributed renewable energy benefits via tailored policies and deployment financing mechanisms (Boz et al., 2015; Santos et al., 2014). The identification of network elements that may potentially experience excess PV technical potential could be used by utilities for planning grid infrastructure upgrades or control measures. Utilities may also be able to identify aggregations of interconnected buildings with enough rooftop solar potential to reduce incoming utility-scale generation (Kodysh et al., 2013).

While this approach is flexible and has broad application potential, it also has limitations and the results should be considered with these in perspective. Importantly, this methodology looks simply at the net overall balance of consumption relative to supply across the electrical network. It does not involve a power flow model, and as such does not explicitly consider voltage, frequency, and reactive power characteristics or the potential impacts of increased levels of distributed renewable energy penetration in terms of grid instability, network infrastructure capacity, and power quality problems. Spatially variable, intermittent distributed renewable energy generation has made the current electrical grid susceptible to power disturbances and increased levels of penetration could lead to cascading failures, an imminent issue facing grid operators (Halu et al., 2016; Kammen & Sunter, 2016). In practice, the integration of a significant quantity of rooftop PV generation capacity will likely require upgrades to the infrastructure, capacity, and flexibility of the existing distribution grid and a suite of enabling technologies to balance the integration of intermittent solar resources, such as integrated energy storage and electric vehicles (P. Gagnon et al., 2016). Similarly, in this case, I evaluate the net consumption (or self-supply capability) at the monthly scale given that the historical consumption data I obtain from SMUD is at a monthly resolution. However, loads and renewable energy production potential vary on much shorter timescales and evaluating the net energy demand at the monthly resolution does not capture imbalances that may occur over shorter durations. Moreover, there are limitations to modeling suitable rooftop area and estimating PV technical potential that have been widely covered in the literature (Hofierka & Kaňuk, 2009; Melius et al., 2013). While this method seeks to minimize error in calculating PV technical potential by using fine resolution solar radiation analysis and a state of the art rooftop area suitability model, it still relies on panel efficiency and performance ratio conversion factors that can’t fully capture actual system output. Finally, the UPLAN model used to simulate future urban growth patterns is deterministic, and thus, the outputs are a direct result of the input feature attractiveness and allocation rules. While I strive to capture important assumptions driving land use decisions via attractors, detractors, constraints, and land class and demographic data, it is difficult to capture all of the drivers of land use development decisions in a simplistic model.

Given the limited research into the implications of a transition to distributed renewable energy for future urban development, there are numerous avenues for further research. As implied by the limitations of this study, repeating this methodology for other pertinent temporal scales is a logical next step. This might include winter months when loads are high for space heating but PV technical potential is lower, or sub-daily timesteps to show how the net energy demand-supply balance across the grid changes throughout the day as loads and solar resources shift. Another relevant avenue for future research would be to more realistically integrate power-flow characteristics and the potential for integrated energy storage technologies into the electrical grid model used in this approach. Moreover, it would be interesting to explore more deeply the assumptions in the urban growth model and develop scenarios around different renewable energy technologies or policy designs. For example, scenarios involving neighborhood-scale ground mounted solar installations or building façade solar generation might lend themselves to different patterns of future urban development. Exploring the effects of FITs or energy zoning policies would also be interesting. Other future research could apply this method to different cities to evaluate if similar trends in patterns of future urban growth occur in varied geographic contexts under the same assumptions. All of these avenues would provide valuable insight to further our understanding of the potential influence of a transition to distributed renewable energy generation on future urban development.

Chapter 5. Conclusion

Notwithstanding beneficial carbon emission reductions, the research presented in this dissertation suggests that the direct and indirect environmental implications of a low-carbon energy transition have the potential to be as revolutionary as those associated with past major energy infrastructure shifts on the order of that spurned by electrification itself. Understanding the potential for future energy scenarios to result in such effects is critical to making informed assessments of the future energy pathways available to society while avoiding unintended environmental consequences. Thus, the approaches I develop herein seek to provide innovative methods to forecast the potential effects of various low-carbon energy system scenarios on both the natural and built environment before they occur. The results of my research indicate a low-carbon transition will shift the location and magnitude of direct impacts on natural resources, as well as influence new patterns of urban, regional, and environmental development. Cumulatively, these findings suggest that in particular, decarbonizing our energy system has the potential to significantly influence future land use and transform landscapes. These findings have vital implications for environmental planning, necessitating a shift in focus towards energy-conscious, proactive intervention at local and regional scales in order to avoid unintended environmental consequences of energy infrastructure transitions and associated urban development.

Broadly, my findings show that a low-carbon energy transition requiring widespread changes in the technologies and networks via which we produce and deliver electrical power can in turn be expected to alter the direct environmental effects of our energy system and modify patterns of urban development. Analyzing the historical relationships between energy, environment, and urban development in the United States in Chapter 2, I find that shifting opportunities and constraints associated with past primary energy source (and accompanying energy infrastructure system) transitions have resulted in significant and varying patterns of direct environmental degradation, as well as changing spatial locations and morphologies of urban development, itself one of the most extreme environmental modifications caused by humans. Recognizing that uncertainty remains over what resources and generation scales a future low-carbon energy system may involve, I present geospatial approaches to forecasting potential direct environmental resource and indirect urban development effects of various future low-carbon energy system scenarios.

In Chapter 3, I temporally and spatially project the potential direct air pollution, water consumption, and land use conversion effects of six future regional energy system scenarios involving centralized and decentralized low-carbon generation sources of different types, under various policy conditions. I find that by 2030, carbon reduction scenarios generally confer co-benefits in terms of reduced region-wide water consumption and pollutant emissions relative to BAU, but require significantly more land conversion. Furthermore, I find that the magnitude of these effects shows wide spatial variation across the region and within individual scenarios, and also varies among the decarbonization scenarios themselves by as much as 108,000 annual tonnes of air pollution, 145×10^9 annual liters of water consumption, and 491,500 cumulative square-hectares of land conversion. In contrast to and expanding upon the analysis in Chapter 3, the approach I present in Chapter 4 is focused on the indirect environmental effects of a transition to distributed renewable energy generation via its potential to shift patterns of urban development. I quantify the effect of a shift to distributed photovoltaic electricity generation on net energy consumption along Sacramento's electrical grid and simulate the resulting influence on patterns of future urban growth in the city. I find that relative to a base growth scenario, a scenario emphasizing distributed rooftop PV integration would have both locally concentrating and regionally dispersing influences on future urban growth and would result in less mixed land uses in favor of diffuse single land use development.

More specifically, these results suggest that, in particular, there is a trend towards significant environmental consequences from additional future direct and indirect land use associated with a low-carbon energy transition—whether generation sources are implemented at largely centralized, decentralized, or a mix of scales. It is widely acknowledged that because the energy density of renewable resources is lower than that of fossil fuels, much larger areas will be required to generate enough energy from renewables to support future demand (Stremke & van den Dobbelsteen, 2013). In the regional context of western North America, I find this to be the case as well. The six future regional low-carbon energy system scenarios I evaluate are projected to necessitate 2.70x106 ha^2 to 2.20x106 ha^2 of cumulative new land use conversion by 2050 (Figure 12). At the low end, that is approximately 8,500 square miles or slightly less than the land area of the state of New Hampshire. More importantly, while decentralized rooftop solar PV energy deployment is often suggested as a means of reducing the new land use conversion footprint required for renewable energy production, I find that even at this generation scale there are indirect, and potentially equally as consequential, land use conversation implications associated with more diffuse future urban development. For example, in my urban growth model scenario that assumes higher than average solar resource and proximity to existing electric lines with excess net solar PV production (relative to existing demand) would be more attractive to future development all else being equal, I find future land use allocation in the City of Sacramento relative to a base scenario includes decreased mixed land use in favor of low-density residential and single use commercial development allocated in a much more dispersed pattern (Figure 30).

The implication of this result for policymakers and environmental planners is theoretically revolutionary. While transportation has long been viewed as the primary driver shaping the built environment to date, my research indicates that moving forward there is potential for low-carbon energy production to play a much greater role in the architecture of landscapes and society's effect on nature. Reducing vehicle miles traveled (VMT) through compact, mixed use urban form has been a primary objective of policymaking and planning for decades with the understanding that diffuse settlements are energy inefficient (Jones, Wheeler, & Kammen, 2018; Owens, 1979). Today, laws such as California's SB 375 seek to achieve GHG reduction goals by reducing VMT and urban sprawl. Yet, efforts to concentrate development involve an inherent tradeoff with solar access for building-integrated renewable energy generation (Ko et al., 2013) and will become less important for GHG emission reductions with the electrification of vehicles and decarbonization of electricity. Jones et al. (2018) point out that by 2050 virtually all electricity must come from renewable sources in order to meet California's climate targets, and as this transition happens, the GHG abatement potential of energy conservation strategies, such as reducing VMT, will decrease relative to switching from fossil fuels to electricity. This points to complex and conflicting climate abatement and urban sustainability goals in the context of a low-carbon energy transition. Addressing such conflicts will require conscious policymaking that accounts for these potential effects, and deliberate planning to avoid unintended environmental consequences.

Proactive planning to avoid unintended consequences becomes even more important when considering that the ubiquitous nature of renewable resources and the associated potential to generate power at or near points of consumption via distributed renewable energy generation not only incentivizes less dense land use to maximize the potential to capture renewable resources, but also further relaxes constraints on the concentration of urban development by reducing proximal dependence on the existing networked energy infrastructure system. While it is unlikely that the existing electrical grid infrastructure will become entirely dispensable, mounting independence from the network is foreshadowed by trends in DG and energy storage. The ability to self-supply electrical demand via co-located renewable energy generation and storage would, at the extreme, allow development to go “off the grid.” But even in the absence of total disconnection, self-supply capability can reduce the line capacity necessary to serve new development, thereby decreasing the cost to locate land uses further from the existing electrical network infrastructure and facilitating more diffuse development. There is historical precedent for such change. A century ago, one might have maintained that connection to wired landline telephone network infrastructure would remain indispensable. Yet today, with cellular wireless, many households no longer have landline telephones, making household interconnection to the telephone infrastructure network increasingly unnecessary.

Other critical infrastructure systems such as wastewater and potable water systems also show the potential to become more decentralized with technologies such as onsite building-integrated wastewater systems. While this dissertation focuses on transitions in energy infrastructure, the infrastructure-urban development-environment relationships conceptualized, and the approaches presented herein, have the potential for widespread application to other such networked infrastructure systems upon which society depends. Overall, the more independent future development becomes from these networked infrastructures, the fewer fundamental constraints will remain on the diffusion of urbanization across landscapes. Planning that considers these effects of a low-carbon energy transition and uses the approaches presented herein to evaluate similar effects of decentralization in other networked infrastructure systems will be critical to avoid potential environmental consequences associated with less constrained development.

The implication that a low-carbon energy transition has potential to impact the environment both indirectly via shifting constraints on urbanization and directly via effects on natural resources, suggests the need for a major reorientation of focus in the practice of urban and environmental planning toward more energy conscious, proactive intervention. According to Stremke & van den Dobbelsteen (2013), the sheer amount of renewable energy needed to sustain humanity may require us to conceptualize every landscape as an energy landscape and the practice of planning has yet to fully acknowledge the complexity inherent in the creation of sustainable renewable energy landscapes. At a basic level, a reciprocal interplay exists between energy, urban development, and the environment—energy and urban development opportunities are influenced by environmental endowments, and energy and urban development choices, in turn, influence the environment (Owens, 1981; J. C. Williams, 1997). Yet, the perception that new energy resources have the potential to effect utopian societal change by providing better, cheaper, infinitely more abundant energy has historically blinded people to the reality of the second half of this interplay (Melosi, 1985; J. C. Williams, 1997). To avoid this pitfall in the context of the burgeoning low-carbon energy transition, the discipline of planning must shift focus from adaption to prevention of environmental consequences.

Moreover, while carbon emission reductions from the electricity sector will confer benefits globally, the research presented herein suggests that the potential environmental impacts of a low-carbon energy transition will occur at local and regional scales. Thus, it is at these scales that planners and policymakers should focus efforts to avoid undesired environmental consequences. In contrast to traditionally top-down energy policymaking, planners have the important responsibility of avoiding possible adverse effects of energy development in local and regional contexts (Owens, 1981). Stremke and van den Dobbelsteen (2013) observe that while energy-conscious environmental interventions can be implemented most effectively at municipal and regional levels, policymaking and planning have often neglected to focus efforts at these scales. Similarly, Jones et al. (2018) stress that urban planning, energy conservation, energy efficiency, and renewable energy all require extensive local participation, and they suggest that from this perspective effective climate change planning should address emissions more comprehensively and more locally. Integrated energy-environment-urban development interventions to prevent or mitigate the undesirable environmental consequences of a low-carbon energy transition are therefore likely to be best informed and most successful when propagated from the bottom-up.

Nearly four decades ago, Van Til (1979, p. 328) advocated that responsible planning for energy transitions must take into consideration the possible spatial and environmental implications of new energy scenarios well in advance, proclaiming “to succeed in the transformation will require early warning, brilliant planning, great leadership.” His call still rings true today. The research I present herein contributes to meeting this need with innovative approaches to understanding and forecasting the potential direct natural resource and indirect urban development implications of future low-carbon energy system scenarios. The potential for transition to low-carbon energy systems presents fundamental choices regarding what resources and generation scales to target. By reducing uncertainty with respect to the possible environmental effects of these choices, this research can aid planners and policymakers in holistically evaluating the energy pathways available to society. Importantly, the results of this work suggest that low-carbon energy production and consumption will be significant drivers of landscape transformation in the future, and that a new planning paradigm—one that is to a greater degree energy-conscious, proactive, and focused on intervention from the bottom up—will be essential to avoiding undesirable, unnecessary conflicts between low-carbon energy development, urbanization, and the environment before they occur. Embracing approaches such as those described in this work is an important step to achieving the brilliant planning necessary to address climate change through transformation to a low-carbon energy sector while also avoiding other unintended environmental consequences.

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