RESEARCH ARTICLE

Deep decarbonization and renewable energy in the Appalachian Mountains (DDREAM): a socio-ecological systems approach to evaluating ecological governance

Stephen P. Mainzer[1] · C. A. Cole[2] · Travis Flohr[1]

Abstract

Through the lens of ecologically based planning and design decisions for a renewable energy infrastructure, our project investigates a pilot method that assesses ecological, geographic, and sociopolitical opportunities and constraints. This method couples an application of the University of Pennsylvania Suitability Analysis Method, more commonly known as the McHarg Method, and a statistical analysis of the Appalachian Mountain Region of Pennsylvania in the United States. Despite the region's high-quality natural resources, persistent reliance on coal industries has resulted in disadvantaged socioeconomic distress and risk. By unraveling linkages between socio-ecological systems and governance actions, the results of our pilot described challenges for the Appalachian Mountain Region in transitioning to a renewable energy infrastructure, while also formulating the basis for county-level strategies that may encourage the pro-environmental governance necessary to promote renewable energy initiatives. We find that Appalachian counties' relatively low levels of infrastructure density, solar irradiation, population growth, limited access to education centers, and high-quality forests present challenges to allocating suitable areas for solar infrastructure. However, clusters of moderately suitable areas are identifiable throughout the region. Yet such opportunities may struggle to support solar energy initiatives as the region suffers from limited pro-environmental governance, particularly in areas with low-density infrastructure and historically higher levels of dependence on natural resource industries. Above all, our findings identify that the relationship between socio-ecological conditions and pro-environmental governance is complex and often in conflict in key areas of the region.

Keywords Pro-environmental governance · Suitability analysis · Renewable energy infrastructure · Appalachian Region · The McHarg Method · Design with nature

1 Introduction

The global imperative of reducing carbon emissions (deep decarbonization) can only be achieved if we substitute sources of energy that do not come from fossil fuels (e.g., wind, solar, nuclear, hydroelectric, and biomass). Investments in energy development are critical drivers of socioeconomic growth (Asakereh et al. 2017, p. 342). Yet we suggest that the socio-ecological conflict inherent in the Appalachian Mountain Region presents significant challenges in transitioning from a fossil-fuel-based economy to renewable infrastructure. Such a transformation will require substantial changes in the way residents think about energy production and corresponding governance actions in rapidly changing political and ecological environments. This study is an extension of the vision set forth through E+D: Ecology plus Design, a new center-in-development at The Pennsylvania State University. It is the initial phase of a larger plan to assess the potential for policies catalyzing renewable energy systems throughout the multi-state Appalachian Mountain Region by exploring the opportunities and constraints, ecologically, geographically, and sociopolitically, through the lens of planning and design. To our knowledge, this represents a uniquely interdisciplinary paradigm of evaluating renewable energy infrastructure.

✉ Stephen P. Mainzer
  spm192@psu.edu

1 Department of Landscape Architecture, The Pennsylvania State University, 121 Stuckeman Family Building, University Park, PA 16802, USA

2 Department of Landscape Architecture, Huck Institute of Life Sciences, The Pennsylvania State University, University Park, PA, USA

Our study attempted to address the complex socio-ecological challenges to growing solar infrastructure in the Appalachian Mountain Region by exploring three questions related to the suitability of solar infrastructure:

1. How suitable is the Appalachian Mountain Region for solar infrastructure in the context of the broader state;
2. Where are the most suitable areas for solar infrastructure in the Appalachian Mountain Region;
3. How do solar infrastructure suitability factors inform pro-environmental governance actions?

To address the first and second questions, we applied the University of Pennsylvania Suitability Analysis Method, more commonly known as the McHarg Method (McHarg 1969; McHarg and Steiner 1998, 2006; Steiner 2008), specifically technical, biophysical, and social dimensions of renewable energy infrastructure. Our approach synthesized factors traditionally included in solar suitability models with an extensive array of socio-ecological systems often championed in design and planning by McHarg and others but rarely included in solar suitability models. To address the third question, we piloted a method of comparing suitability data to voting actions recorded in the recent 2018 Midterm General Election. Though imperfect in the coarseness of the available data and the somewhat unique nature of Pennsylvania as a commonwealth state, the use of widely available secondary-source governance data adds an important and novel perspective on how we interpret suitability results toward developing design and planning strategies for transitioning to a renewable energy infrastructure in the Appalachian Mountain Region.

1.1 Appalachia's socio-ecological conflict

We selected the Appalachian Mountain Region as our area of study for two reasons. First, the region experiences a complex array of environmental, economic, and cultural challenges in transitioning from long-held traditions of fossil fuel extraction. Second, the region has a rich, easily accessible dataset that illustrates many of these challenges suitable for our pilot study. In the USA, the Appalachian Mountain Region runs from Alabama through Maine, a distance of 1400 miles. Along the region exist some of the highest levels of biodiversity and some of the most intransigent levels of human poverty. The official Appalachian Region covers 13 states as defined by the Appalachian Regional Commission (ARC 2019) extending along the US eastern coast from New York to Mississippi. In the northern portions of Appalachia, and particularly in Pennsylvania (see Fig. 1), the region has long been a source of natural resources as timber, coal, oil, and now, natural gas extraction. Yet, recent trends illustrate that coal production in the region is declining rapidly and

jobs are disappearing at a steady rate (Carley et al. 2018). These activities have left the landscape scarred and the residents dealing with the environmental consequences. The landscape shows abandoned and partially reclaimed mined lands, streams affected by acid mine drainage, and an increasing number of miles of natural gas pipelines fragmenting the forest cover.

While in some ways the socio-ecological composition of the Appalachian Mountain Region is unique, for several reasons the region is generalizable to rural areas both nationally and internationally. First, it is the heart of coal mining in the eastern USA and has been for generations. Culture often revolves around mining for coal. It is a chronically poor region almost totally dependent upon extraction of natural resources (e.g., coal, timber) for its economic livelihood. Despite containing some of the state's highest quality natural resources (Albright et al. 2014), the Appalachian region is characterized as disadvantaged across social and economic trends (ARC 2019). Finally, it has become a politically conservative region, whose residents have become increasingly suspicious of government policies and programs intended to "help" the region. These are the reasons we chose to work in Appalachia and why the region serves as a test case for other parts of the world.

1.2 Energy and governance context

We sought to pilot solar infrastructure as a resource that has yet to be optimized in a region with a strong social need for economic development but little existing momentum beyond several goal-setting efforts. Pennsylvania ranks second in the USA in total energy production, largely driven by natural gas extraction and nuclear facilities. Despite recent downturns in the industry, a significant amount (18.8%) of the state's production still comes from coal mining. Renewables yield just 4.4% of the state's utility-scale net generation. Nearly half of all renewable energy generated comes from wind power (Energy Information Administration 2018), including several new wind farms (Jacquet 2012, p. 680) while approximately a quarter is produced from hydro- and biomass. Solar energy produces less than 1% of the state's net electricity (Energy Information Administration 2018). In 2004, Pennsylvania adopted the Alternative Energy Portfolio Standard (AEPS) establishing a requirement that 18% of electricity shall be generated by renewable sources, with at least 0.05% from solar energy by 2021 (Energy Information Administration 2018; Alternative Energy Portfolio Standards Act 2004). While Pennsylvania is on pace to achieve this share of solar generation, this goal falls far behind neighboring states. Pennsylvania's Department of Environmental Protection established a more ambitious goal—a 10%
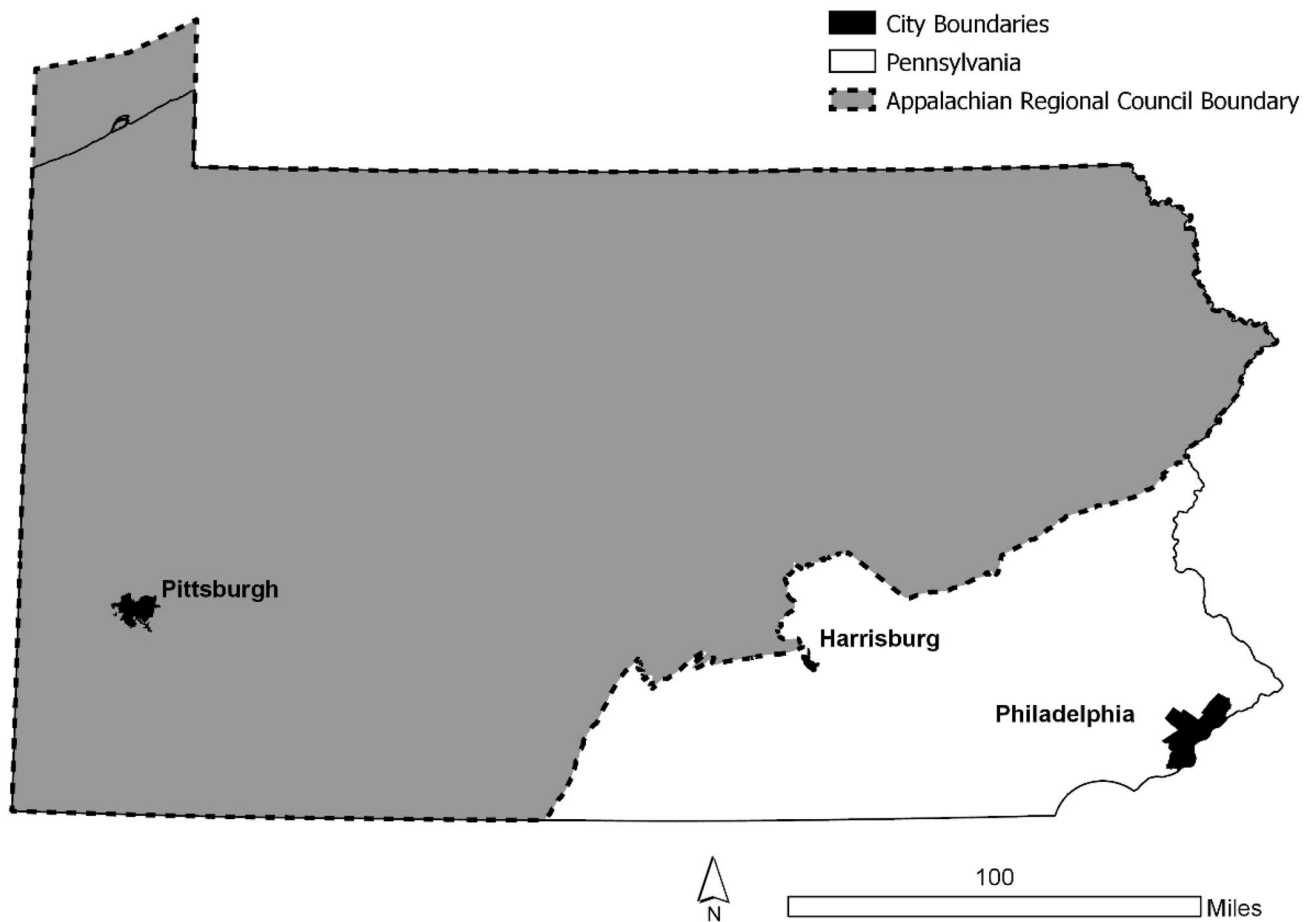
Fig. 1 The Appalachian Mountain Region of Pennsylvania

increase in solar generation by 2030. Achieving that goal will require converting just 124 square miles to utility-scale solar infrastructure (Pennsylvania's Solar Future Plan 2018).

We adopted the term *pro-environmental governance* to describe collaborative networks with a public purpose of minimizing environmental impacts. In this case, we are specifically interested in individuals' participation in the collaborative actions of governance that may encourage future solar infrastructure that meets Pennsylvania's energy goals and results in a drawdown of carbon emissions. Pro-environmental behaviors are conscious actions taken by individuals that minimize their impacts on the natural environment (Kollmuss and Agyeman 2002, p. 240; Park and Ha 2012, p. 389) or on the "availability of materials or energy" in the environment (Stern 2000, p. 408). However, the power of individuals to address significant environmental challenges is limited, resulting in a need to form collaborative networks—or a "set of actors linked by a set of ties." Governance describes networks specifically focused on public policy that collaboratively

pursue a public purpose (Barriutia and Echebarria 2019, p. 109).

Pennsylvania is one of four states in the US that is technically a Commonwealth. The distinction in Pennsylvania lies in how political power is distributed throughout the state. For the Commonwealth of Pennsylvania, political power has been distributed in part to the 67 counties, but local decision-making reigns supreme in Pennsylvania. There are 2562 municipalities in Pennsylvania, each one with the power to regulate land use. This fractured distribution of political power makes it difficult to develop comprehensive plans across municipal boundaries. Planning in Pennsylvania can occur at the local level, but comprehensive planning often occurs only at the county level, especially in rural areas of the state. However, given the sheer number of municipalities in Pennsylvania, one can readily imagine the difficulty in developing any plans that address environmental issues on a regional level. Environmental governance actions by smaller municipalities only apply to a small area of land of the municipality itself and might be countermanded by the neighboring municipality. Despite the emphasis on

municipal-level decision-making, we found that the Department of State (2019) did not certify voting records for the 2018 Midterm General Election at a scale below the county level. It was for these two reasons—the need for comprehensive planning at the county scale and availability of data—that we focused on the county as a unit of analysis.

2 Methods

We developed two models that incorporated the technical, biophysical, social, and governance dimensions related to the suitability of solar infrastructure. The first was a GIS-based multi-criteria model designed to explore the questions of how suitable the Appalachian Mountain Region is for solar infrastructure and where the most suitable areas are. We adapted the McHarg Method of land use suitability analysis (McHarg 1969; McHarg and Steiner 1998, 2006; Steiner 2008) to identify optimal areas for new solar infrastructure throughout the state. The second was a statistical model that compared suitability data to recent governance actions exhibited by each county's residents in the recent 2018 Midterm General Election results. To be clear, our aim is not to develop a site selection model for solar suitability. Rather, we intended to explore the suitability of "invest-in-solar" policies based on socio-ecological conditions. While it is a challenge in a Commonwealth state, a county-level analysis matches our intent, the availability of data, and our scope for processing such data. As such, we expected to observe challenges and opportunities at the intersection of suitability and governance at the county level that provides insight into how strategies might be developed to support future solar energy initiatives.

The McHarg Method of land use suitability analysis evaluates a series of comprehensive factors in terms of their suitability for specific land use objectives. Our review of the extant literature revealed that solar suitability factors are typical derived from three major groupings: technical factors required for ease of installation and optimal solar production, biophysical factors necessary to protect critical natural and cultural resources, and social factors that describe human capital (Asakereh et al. 2017, p. 345; Castillo et al. 2016, p. 87; Brewer et al. 2015, p. 828; Watson and Hudson 2015, p. 23; Stoms et al. 2013, p. 292; Charabi and Gastli 2011, p. 2559; Baban and Parry 2001, p. 65). There is general agreement about specific technical factors to include in solar suitability analyses—yet the consensus about biophysical and social factors is less clear. McHarg and Steiner (2006, 1998), McHarg (1969) and Steiner (2008; McHarg and Steiner 1998) argue that a robust array of biophysical and social factors is necessary to inform large-scale landscape planning. Implementing either utility-scale or small-scale solar infrastructure at sufficient levels to meet

Pennsylvania's solar energy goals will require significant land use changes, ideally in areas with opportunities for optimized uses, such as pastures, abandoned mines, or other disturbed lands (Pennsylvania's Solar Future Plan 2018, p. 6). Solar investments are expected to have powerful economic impacts in the form of 60,000 to 100,000 new jobs with median wages between $20 and $38 per hour (Pennsylvania's Solar Future Plan 2018). These land use and employment impacts have the capacity to transform areas to meet development goals. In response, our pilot model attempts to incorporate a wide series of socio-ecological data pertinent to the Pennsylvania landscape with the understanding that parts of this dataset are experimental and may be more or less useful in describing solar potential.

We developed a multi-criteria GIS model (Asakereh et al. 2017; Castillo et al. 2016; Brewer et al. 2015; Watson and Hudson 2015) to produce the suitability data through two steps. First, we evaluated most factors as a heterogeneous layer in terms of least-to-most suitable for solar infrastructure and coded along a corresponding number scale (1 = least suitable, 5 = most suitable). Layers were overlaid to illustrate spatial congruencies among most and least suitable areas throughout the state using ArcMAP's Raster Calculator. Second, factors that were determined to be constraints to solar infrastructure (such as wetlands or the highest level of ecological or cultural conservation) were removed from the data by a Boolean process, resulting in a score of zero. The following describes the rationale for each layer and key decisions made in preparing data for analysis.

2.1 Technical factors

Technical factors included *transportation network, energy grid,* and solar irradiation or *direct normal irradiance* (*DNI*). There is consensus that these factors are critical for solar suitability studies and that solar irradiation should be the most prioritized among them. However, there is disagreement about how to weight the remaining factors (Asakereh et al. 2017, p. 345; Castillo et al. 2016, p. 87; Brewer et al. 2015, p. 828; Stoms et al. 2013, p. 292; Charabi and Gastli 2011, p. 2559). Slope is also typically included in such studies, though the scale of transforming topographic data for the entire state was beyond the technical scope of our pilot study.

New solar facilities would ideally be located close to both roadways and transmission utilities in the interest of minimizing the construction of new supporting infrastructure and impacts on existing natural resources. We constructed buffers at one-eighth, one-quarter, and one-half mile around all electric power transmission lines identified by the Homeland Infrastructure Foundation-Level Data (HIFLD). The density of the statewide roadway network required a broader approach. The state was divided in one-quarter acre cells. Each was coded based on the presence of a state, local, or

unpaved road. Solar potential for the state was provided by the US Department of Energy's National Renewable Energy Laboratory (NREL) direct normal irradiance (DNI). All of the state falls within the NREL's classification of "good" (4–5 kWh/m^2/day) (Asakereh et al. 2017, p. 347). While the NREL's classification system bodes well for the state's solar future, it does not support our goal of identifying the most suitable locations in the state. Instead, we coded the DNI data according to standard deviation from the mean to force an illustration of areas that were demonstrably better than average (Table 1).

2.2 Biophysical factors

Our analysis sought an environmental ethic of avoiding locations with prime natural resources. Previous solar suitability studies have identified a need to protect valued natural resources from infrastructure development. However, we found that these studies typically evaluate biophysical data as homogenous layers in a manner that masks the dynamic quality of biophysical factors. For example, the US Geological Survey Gap Analysis Project (GAP) identifies four levels of conservation based on biodiversity. Conservation limitations within these classifications vary in terms of management and may include being accessible for resource extraction (Gergely et al. 2019, p. 2). As such we evaluated biophysical data in two ways; for constraint layers, we identified discreet areas to be removed through a Boolean process, and for non-constraint layers we classified characteristics along a scale from most-to-least suitable. Biophysical factors included *key land uses* (Watson and Hudson 2015, p. 25; Charabi and Gastli 2011, p. 2559; Baban and Parry 2001, p. 5), *farmland quality* (Asakereh et al. 2017, p. 345; Watson and Hudson 2015, p. 25), *forest quality* (Steiner 2008, p. 99), *hydrological factors* (Asakereh et al. 2017, p. 345; Castillo et al. 2016, p. 87; Steiner 2008, p. 71), *geology* (Steiner 2008, p. 71), *US Geological Survey Gap Analysis*

Project (GAP) status (Castillo et al. 2016, p. 87; Watson and Hudson 2015, p. 25; Baban and Parry 2001, p. 5), and *federal and state conservation lands* (Asakereh et al. 2017, p. 345; Watson and Hudson 2015, p. 25). Land use data acquired from the National Land Cover Database identified barren and shrub/herbaceous lands to be coded as very suitable and moderately suitable accordingly. Prime farmland, and farmland of state, local, and unique importance were identified from USA Farm Class data. Forest quality data were provided by the US Department of Agriculture as a matrix describing the distance of core forest from roadways. Cells of forestland furthest from roadways were coded for preservation as least suitable. Small, but critical lower Strahler Order streams were deprioritized by creating a 1/4 mi buffer around all streams and waterways and coding the lowest order streams less suitable than the highest order streams. Concentric buffers were created around all active groundwater sites to maximize protection of valuable aquifers. Geological data were coded to avoid sinkhole risks in limestone-rich karst areas. Last, we assessed the various levels of protection currently cited by GAP status, federal, and state conservation areas. The more restrictive ecologic, cultural, historic, and recreation resources were coded as less suitable accordingly. The most restrictive conservation areas, wetlands greater than 10 acres, and existing water bodies were coded as not suitable (Tables 2, 3).

2.3 Social factors

We found broad support for including social factors in suitability analyses but few specific recommendations. Castillo et al. (2016) and Stoms et al. (2013) suggested a buffer around urban areas to avoid land use conflicts and "resistance of local communities" (Castillo et al. 2016, p. 88). Our study differed in that we sought to compare suitability and potential resistance through pro-environmental governance actions, and so we did not include measures of resistance in

Table 1 Evaluation matrix of technical factors

	Data date	Not suitable	Least suitable	Somewhat suitable	Most suitable
Transportation network	2018				
State roads					•
Local roads				•	
Unpaved roads			•		
Energy grid	2017				
1/2 mi				•	
1/4 mi				•	
1/8 mi					•
Direct normal irradiance (DNI)	2016		< − 1.5 SD	< − 0.5 SD	> 0.5 SD	> 1.5 SD

SD standard deviation from the sample mean

Table 2 Evaluation matrix of biophysical factors

	Data date	Not suitable	Least suitable	Somewhat suitable	Most suitable
Land use classification	2011				
Water		•			
Shrubland/herbaceous				•	
Barren					•
Farmland quality	2017				
Prime farmland			•		
State importance				•	
Local importance				•	
Unique importance				•	
Not farmland					•
Forest quality	2011				
> 700 m			•		
> 500 m				•	
> 100 m				•	
< 100 m				•	
Not forest					•
Hydrology					
Wetlands (> 10 acres)	2009	•			
Stream classification	1998				
< 3			•		
< 5				•	
< 8				•	
Ground water	2018				
1/2 mi			•		
1 mi				•	
5 mi				•	
> 5 mi					•
Geology	2016				
Limestone			•		
All other formations					•
GAP status	2016				
Managed—1		•			
Managed—2			•		
Subject to extractive				•	
No protection				•	
No GAP status					•
Federal conservation lands	2018				
Conservation		•			
Forest, hunting, and wild lands			•		
Historic				•	
All other conservation lands				•	
No conservation					•

the suitability analysis. Watson and Hudson's (2015) model avoided residential areas, though we felt such a constraint misses an opportunity to explore whether the future of solar in Pennsylvania lies in utility-scale or smaller-scale installation. Steiner (2008) states that population trends are an important factor in planning for socioeconomic growth (p. 150).

In our assessment, these social factors did not fully address the challenge of evaluating solar suitability in a rural area, specifically the socioeconomic conditions of

Table 3 Evaluation matrix of social factors

	Data date	Not suitable	Least suitable		Somewhat suitable		Most suitable
Population change	2016, 2012		<−1.5 SD	<−0.5 SD		>0.5 SD	>1.5 SD
Unemployment	2016		<−1.5 SD	<−0.5 SD		>0.5 SD	>1.5 SD
Industry dependence	2016		<−1.5 SD	<−0.5 SD		>0.5 SD	>1.5 SD
Education (*Bachelor's degree or higher*)	2016		<−1.5 SD	<−0.5 SD		>0.5 SD	>1.5 SD
Education centers	2016						
75 mi			●				
30 mi				●			
15 mi					●		
10 mi						●	
5 mi							●

SD standard deviation from the sample mean

the Appalachian Mountain Region. Rather, we included an experimental series of social factors to assess the need and ability to manage the transition to a renewable energy infrastructure. These factors included *population change, unemployment, education, education centers, industry dependence,* and *a pro-environmental governance index.* Our model prioritized counties that were actively growing between the most recent 5-year period recorded by the American Community Survey (2012–2016), and areas that were suffering from higher levels of unemployment. Understanding that transitions require changes in the labor force, we sought counties with higher percentages of residents who had earned bachelor's degrees. We assumed that such transitions would also require additional training programs and access to secondary and above education centers located by the National Center for Education Statistics' (NCES) Education Demographic and Geographic Estimate (EDGE) no further than a one-hour drive, or approximately 75 miles. Pennsylvania's long history of reliance on natural resource industries was a key factor in identifying in the most need of transition. Counties with a higher percentage of employment from a natural resource industry (agriculture, forestry, fishing and hunting, and mining as defined by the US Census data) were coded as more suitable for new infrastructure.

2.4 Model weighting and validation

Other than a general agreement among the literature that the most important factor for solar suitability was solar irradiation, we found little guidance in the weighting of our experimental biophysical and social factors. Given our robust expansion of biophysical factors and social factors, we opted to pilot a simple factor weighting scheme that emphasized the importance of technical factors (see Table 4). We then validated the results of the suitability model following a

Table 4 Model weighting

Suitability factors	Weighting	Constraint layers
Transportation network	0.50	Water
Energy grid	0.50	Wetlands (> 10 acres)
Direct natural inference (DNI)	1.00	GAP Status (managed-1)
Barren	0.25	
Shrubland/herbaceous	0.25	
Farmland quality	0.25	
Forest quality	0.25	
Stream classification	0.25	
Ground water	0.25	
Geology	0.25	
GAP status	0.25	
Federal and state conservation lands	0.25	
Population change	0.25	
Unemployment	0.25	
Education	0.25	
Education centers	0.25	
Industry dependence	0.25	

method outlined by Castillo et al. (2016). We first assigned suitability scores to the 27 existing solar plants in Pennsylvania based on the location of the plant within one of the model's cells. Then we randomly located five sets of 27 points and calculated the average suitability score for each. Both series were tested for normality using the Shapiro–Wilk test and compared by a one-sample *t* test.

2.5 Pro-environmental governance data

The above factors provide a comprehensive description of Pennsylvania but do not describe potential levels of support

for solar infrastructure. To address this critical factor, we created a pro-environmental governance index that summarizes a county's support for the pro-environmental platforms of elected officials. We first attempted to develop an aggregate environmental rating for all US and state-level candidates in the 2018 Midterm Elections. However, as a result of inconsistencies in available ratings across the various levels of races due to rapid changes in data availability during and immediately following the election, and inconsistent data about candidates from state and local elections, we limited our evaluation to 2018 US Senate candidates.

For each candidate, we averaged a balanced series of partisan reviews of the candidates environmental platform and actions (provided by https://votesmart.org/), including the Conservative Review, Americans for Prosperity, Campaign for Working Families, Heritage Action for America, The John Birch Society, The American Conservative Union, Clean Water Action, Outdoor Industry Association Political Action Committee, Defenders of Wildlife Action Fund, Environment America, Food Policy Action, and the League of Conservation Voters. We then multiplied the candidate's rating by the percentage of votes received for each county in the state to produce a relative index of the county's support for a candidate's pro-environmental platform. We selected the county as the unit of analysis because the Pennsylvania Department of State (2018) certifies election results reports at only the county and statewide level.

The 2018 Midterm General Election was seen by many as a response to broader concerns about the current White House administration. Our data cannot isolate state versus federal drivers, but it does show that when comparing state voting data for US Senators in general elections between 2000 and 2018, the most recent election was not so much a liberal outlier as it was a regression to the mean. Over the last nearly 20 years, Pennsylvanian counties have swung their support for Democratic and Republican candidates (see Fig. 2) in some cases to dramatic results. For example, in 2018 ten counties voted in favor of the Democratic candidate, more than one standard deviation above their 8-year average. The previous year 23 counties voted for the Republican candidate in excess of one standard deviation. While the 2018 election certainly leaned significantly toward liberal candidates, this was not outside the historic norms of the state, although it may suggest that support for pro-environmental platforms is fleeting.

2.6 Statistical model

Our statistical model emerged from an exploration of the significant differences between suitability data and relationships between technical, biophysical, and social dimensions and pro-environmental governance. Data for the analysis were created by calculating the average statistic for each suitability factor, including the overall suitability score, for each county through ArcMAP's Zonal Statistics tool. We then explored correlations between factors and the pro-environmental governance index. To test the explanatory power of significant findings for each dimension, we performed a block regression analysis across five models.

3 Results

The results of the validation tests revealed that the suitability model effectively identified suitable areas for solar infrastructure. The one-sample t test yielded a p value (< 0.00) less than the significant level (0.01), with the mean value of the randomly located points (15.57) being lower than the existing solar plants (17.43) with a 95% confidence interval between -2.49 and -1.23.

Our study asked three questions: How suitable is the Appalachian Mountain Region; where are the most suitable areas; and how does suitability compare to pro-environmental governance? We defined counties in the

Fig. 2 Past US Senator General Election Results, 2000–2018. Note: the left axis represents the number of counties whose number of votes were more than one standard deviation from their 18-year mean
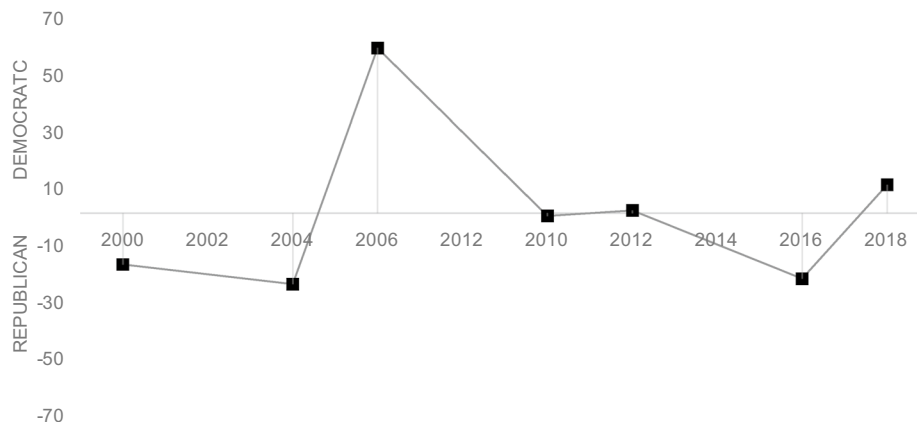
Note: the left axis represents the number of counties whose number of votes were more than one standard deviation from their 18-year mean.

Appalachian Mountain Region as those recognized by the Appalachian Regional Council (ARC 2019). First, we found both graphic and statistical results suggesting that ARC counties are less suitable for solar infrastructure compared to the overall statewide area. More than 94% of the region was classified as marginal or poor suitability (see also Fig. 3). Just 0.004% of the region is rated as highly suitable, which amounts to approximately two square miles. A one-sample t test revealed that the mean suitability score for the region (2.50) is significantly less than the statewide mean (2.68), yielding a p value (< 0.00) less than the significant level (0.01) with a 95% confidence interval between -0.24 and -0.12. A comparison between the mean values of statewide and ARC county suitability factors illustrated stark differences in the socio-ecological composition of the state that contributed to limited opportunities for solar infrastructure. The results described the ARC counties as lacking infrastructural density, solar irradiation potential, and constrained by high-quality forests, slow population growth, and access to education centers (see Table 5).

Second, though opportunities are limited, several locations within the ARC appear to display patches of moderate suitability. Allegheny, Greene, Indiana, Monroe, and Washington counties rank in the top 20 in the state and are the most suitable counties within the ARC area. Each shared a common spatial pattern of moderately suitable linear patches along major state roadways. Regarding the key factors listed above—except for Allegheny county's relatively dense roadway network, energy grid, and numerous educational centers—the other counties did not appear to share a common series of exemplary characteristics. Rather, it appeared that the moderate suitability of the counties was driven by an amalgamation of slightly better than average factors (see Table 6).

Third, our comparison of suitability and pro-environmental governance depicted significant conflicts throughout the state, particularly within the limited solar opportunities of the ARC region. The contrast between the ARC counties and non-ARC counties pro-environmental indexes was less stark than the differences in their socio-ecological characteristics. Both areas contain counties that produced high, average,
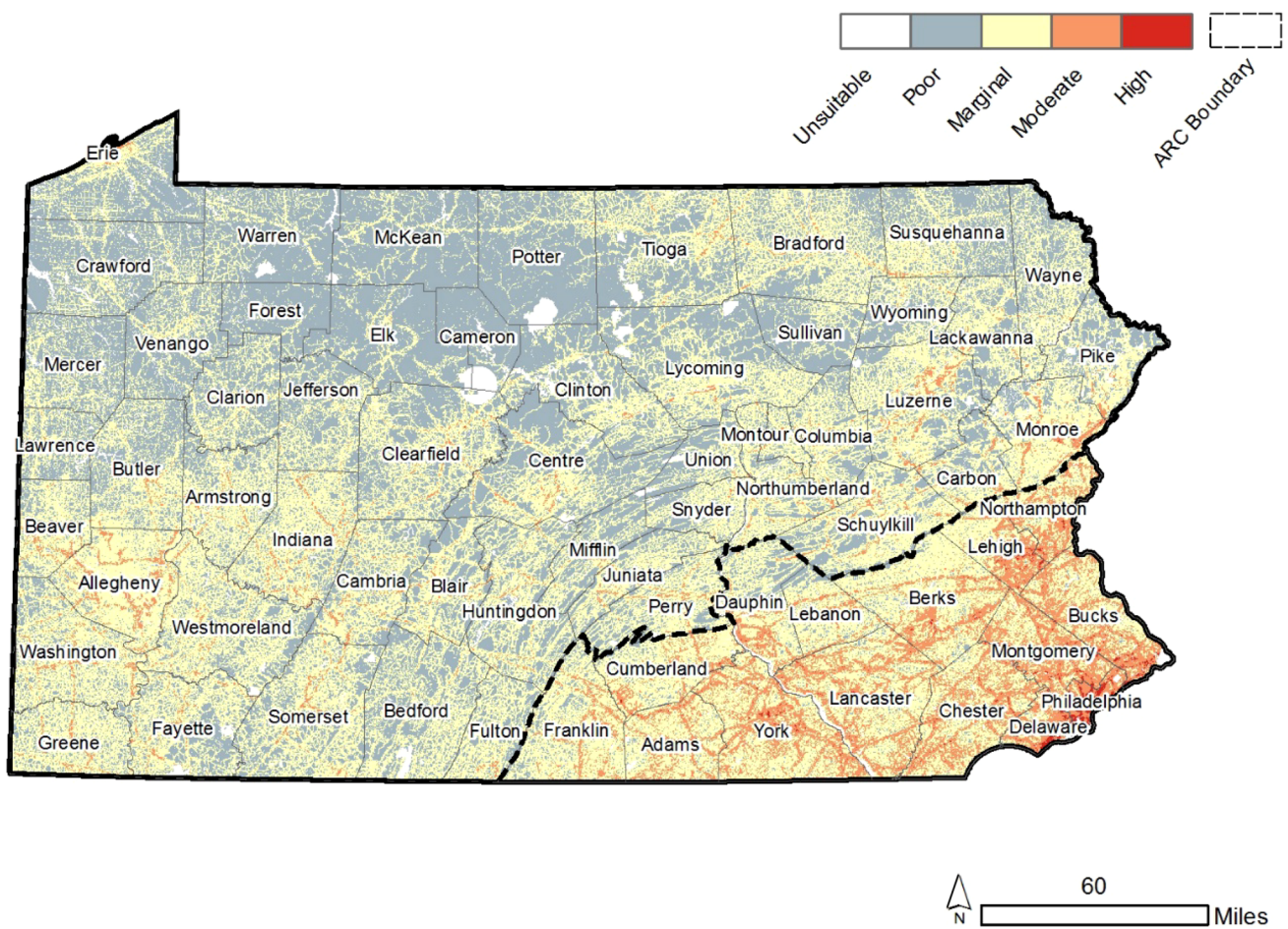

Fig. 3 Suitability model results

Table 5 Comparison of the mean values of statewide and ARC county suitability factors

	State (n = 67)	ARC (n = 52)	Difference (%)
Mean suitability score	2.68	2.50	
Technical			
Transportation network	2.69	2.46	23
Energy grid	0.63	0.50	13
Direct normal irradiance (DNI)	3.14	2.71	43
Biophysical			
Barren lands	0.02	0.02	0
Shrub and herbaceous lands	0.02	0.02	0
Forest quality	3.95	3.78	17
Farmlands quality	3.56	3.68	− 13
Streams	3.05	2.98	6
Groundwater	2.81	2.94	− 13
Geology	4.78	4.82	− 4
GAP status	4.63	4.58	5
State conservation lands	4.73	4.68	5
Federal conservation lands	4.92	4.91	1
Social			
Population change	2.08	1.97	11
Unemployment	2.02	2.06	− 4
Education centers	3.53	3.29	23
Education	2.93	2.97	− 4
Industry dependence	1.91	2.01	− 10

and low pro-environmental index scores (see Fig. 4). Not surprisingly, high index counties appeared to be home to urban areas and/or universities. Yet a simple comparison of the spatial allocation of suitability scores and pro-environmental indexes revealed multiple opportunities and conflicts in the state and ARC counties. The most suitable counties located in the southeast of the state were also among the most pro-environmental. However, two counties in the same area, Lancaster and York counties, were among the least pro-environmental. An ample number of other highly pro-environmental counties make this less problematic in the southeast area. The ARC region shares a similar, though more concerning narrative. While Allegheny and Monroe

counties appeared to be highly pro-environmental, Greene, Washington, and Indiana were much less pro-environmental. Few counties in the region reported better than marginal suitability scores; it appeared that fewer still are likely to be supportive of pro-environmental initiatives.

An analysis of correlations between suitability factors and the pro-environmental governance index illustrated the underlying drivers of these conflicts (see Table 7: Comparison of correlations between suitability factors and a pro-environmental governance index). While there were many significant relationships between suitability factors and pro-environmental governance—including the overall suitability score—for the state, few correlations emerge within ARC counties. Moderate and high suitability scores were more abundant in the non-ARC southeastern area of the state, suggesting stronger connections between common socio-ecological characteristics and pro-environmental indexes. Socio-ecological characteristics likely to correlate with stronger pro-environmental support in ARC counties included a denser energy grid, access to educational centers, higher levels of education, and most significantly, limited reliance on natural resource industries.

Despite numerous relationships across the state, few were uniquely likely to explain pro-environmental governance. A cross-correlation analysis revealed that nearly every suitability factor was correlated with every other factor (p value < 0.05). While this diminishes the importance of the previous finding, it follows common sense. Biophysical factors, including the built environment, and social dimensions of the landscape are linked tightly together by ecological connections within sociocultural systems. It would be more surprising to see data gathered from a non-simulated landscape that did not have pervasive ecological links. Such significant cross-correlations simply confirmed that our data were from the real world.

Given the prevalent cross-correlation of factors, we conducted a block regression analysis of all significantly correlated factors—organized by ARC status, technical, biophysical, and social groupings, to isolate relationships between suitability factors and pro-environmental governance. The results illustrated that several factors preserved significant explanatory power to explain pro-environmental governance

Table 6 Statewide ranking of the most suitable ARC counties

	Allegheny	Monroe	Greene	Indiana	Washington
Transportation network	**4**	**28**	**24**	**27**	**14**
Energy grid	**6**	37	34	**11**	**13**
Direct normal irradiance (DNI)	**28**	**18**	33	41	**29**
Forest quality	**11**	43	34	**30**	**21**
Population change	**10**	43	64	**32**	38
Education centers	**3**	33	39	38	**24**

Bold numbers demarcate a rank higher than the median number of counties (33) in the state
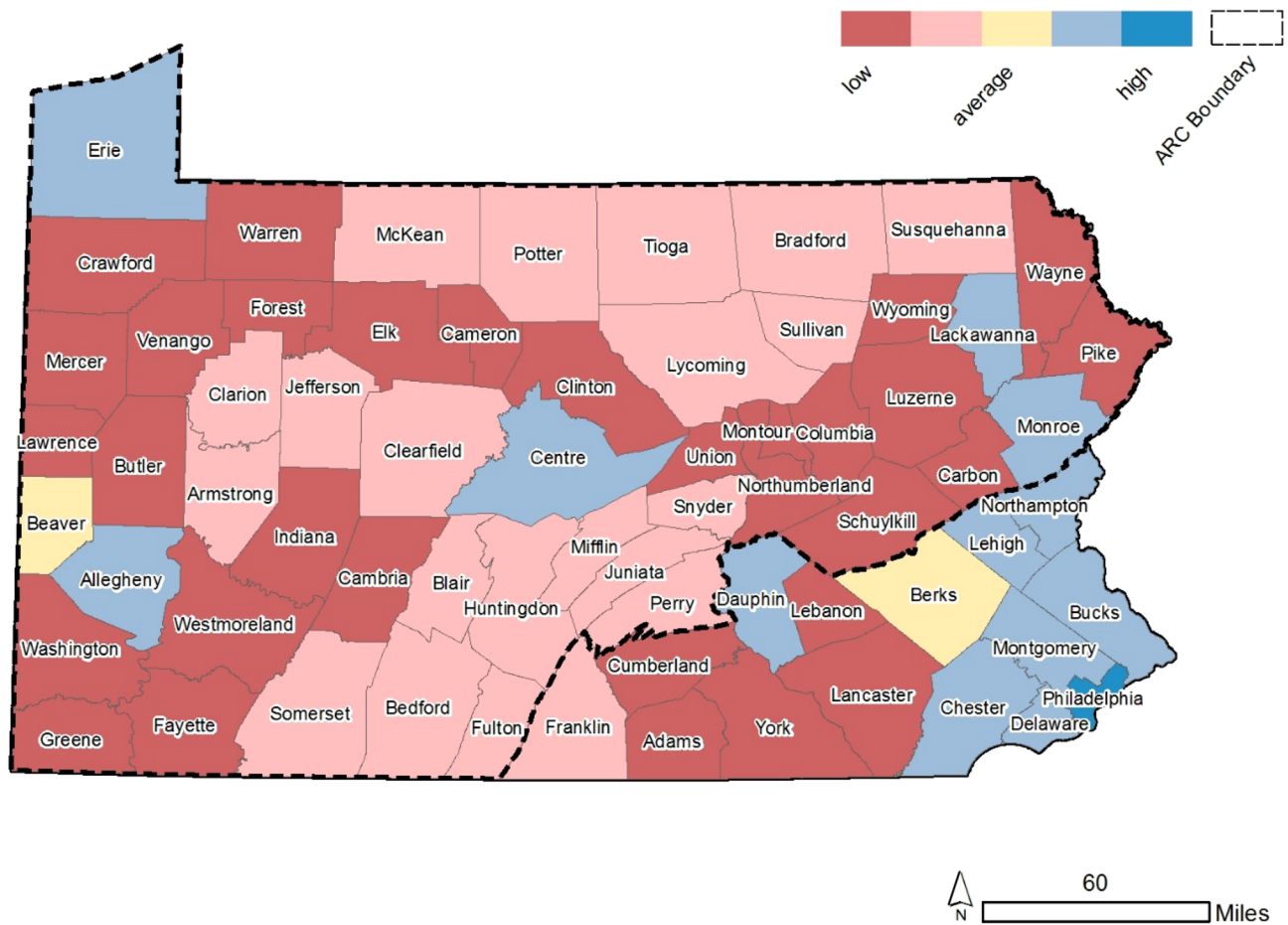
Fig. 4 Pro-environmental index results

($r^2 = 0.55$) and appeared to support previous findings characterizing the challenges of solar suitability in ARC counties (see Table 8). ARC counties again are negatively correlated with pro-environmental governance. Across the state, factors likely to contribute to pro-environmental governance included a denser energy grid, higher-quality farmland, and less reliance on natural resource industries. Notably, only one of these factors—the energy grid—was a key driver of differences in suitability scores between ARC counties and the rest of the state.

Table 9 illustrates a discrepancy between ARC counties with the highest suitability scores and the counties with the highest scores for dependent variables likely to be linked to pro-environmental governance. Ideally, the most suitable counties would also illustrate signs of likely support for pro-environmental governance by ranking among the highest in these key factors. Three out of the five counties share a relatively dense energy grid and Allegheny county ranks in the top five in two categories: energy grid and industry dependence. Yet Greene, Indiana, and Washington counties rank in the top five in only one category. Monroe county—the

only ARC county to contain highly suitable areas compared to non-ARC counties—does not fall into the top five for any categories.

4 Discussion and Conclusions

Our study attempted to demonstrate the utility of suitability data in informing strategies for transition to a renewable energy infrastructure in the context of the Appalachian Mountain Region, an area with complex socio-ecological challenges. We found significant challenges to implementing solar infrastructure in the Appalachian Mountain Region related to the spatial composition of its socio-ecological and governance characteristics. First, the Appalachian Mountain Region is less suitable for solar infrastructure compared to the state. Just 1.4% or two square miles of the region is highly suitable—a very small effort toward the state's goal of 124 square miles of new utility-scale solar infrastructure. However, the region contains ample (995 square miles) of moderately suitable areas. Second, Allegheny, Greene,

Table 7 Comparison of correlations between suitability factors and a pro-environmental governance index

	State (n=67)	ARC (n=52)
Suitability score	0.605**	
Technical		
Roadways	**0.590***	0.270*
Energy grid	**0.618***	0.307**
Direct normal irradiance (DNI)	**0.441***	
Biophysical		
Barren lands		
Shrub and herbaceous lands		
Forest quality	**0.476***	
Farmlands		
Streams	0.350**	
Groundwater	**−0.456***	−0.233*
Geology		
GAP status	0.240**	
State conservation lands	**−0.347***	
Federal conservation lands		
Social		
Population change	**0.342***	
Unemployment		
Education centers	**0.472***	0.274**
Education		0.317**
Industry dependence	**−0.524***	**−0.378***

Bold values indicate significance less than 0.01

***Significant at the 0.01 level

**Significant at the 0.05 level

*Significant at the 0.10 level

Indiana, Monroe, and Washington counties emerged as the highest scoring areas in the region, though each displayed a complex mix of socio-ecological conditions with few consistent characteristics. Third, conflicts between suitability and pro-environmental governance exist statewide. Specifically, Greene, Indiana, and Washington counties present challenges to supporting future solar initiatives in the Appalachian Mountain Region.

We identified seven factors that appear to inform socio-ecological challenges in the region: solar irradiation, infrastructure density (including the energy grid and roadway network), forest and farmland quality, population growth, access to education centers, and reliance on natural resource industries. The ideal socio-ecological conditions to encourage future investments in solar infrastructure are areas that receive high levels of solar irradiation, contain a dense network of roadways and electrical transmission lines, are not limited by valued forest or farmlands, are rapidly growing with access to multiple education centers, and are not historically reliant on natural resources. Unfortunately, this

description does not fit the typical Appalachian landscape. This is most apparent in the emergence of Allegheny county, home to Pittsburgh and its adjacent suburbs, as the most suitable county in the Appalachian Mountain Region. While technically located within the ARC boundary, the county shares little in common with its neighboring counties, let alone the significantly more rural areas of the region. According to the ARC's designations (2019), Allegheny is one of the few "competitive" counties in the region, compared to the much more common "transitional" status. These counties continue to face significant challenges in overcoming their socio-ecological limitations. For example, Monroe county is in transitional status, reported moderately high suitability scores, and displayed high pro-environmental support. Yet the county ranks better than average for only two of five key suitability factors, though one is the critical solar irradiation factor. Further, support in the county may be fleeting. Despite current high levels of pro-environmental governance, support in Pennsylvania has been dynamic over the last 18 years and Monroe did not rank in the top five of any factors likely to influence pro-environmental governance.

The resulting scenario is a classic wicked environmental problem—one that requires a transdisciplinary effort to mediate environmental conditions and social values (Balint et al. 2011). In order to transition from an aging fossil fuel economy to a sustainable renewable energy infrastructure, the Appalachian Mountain Region must contend with its dichotomy of high-quality natural resources and its current areas of pro-environmental support. In describing the challenges of an effective solar suitability analysis, McHarg and Steiner (1998, p. 138) describe a central concept and flaw in the process:

> The moral of the story is that the solution varies with respect to the value system of the person who solves the problem. So you have to identify the interactive biophysical culture system under study

We have attempted here to describe a comprehensive picture of the socio-ecological landscape of the Appalachian Mountain Region sufficient to capture interactions between the biophysical and cultural systems of the study area. Our study revealed that a robust inclusion of factors revealed important nuances in the socio-ecological conditions of the state; however, suitability analysis is ultimately limited by how well the model is calibrated to the local values of the study area. Balint et al. (2011) similarly argue that addressing a wicked environmental problem is an exercise in mediating conflicting values. In our experimental approach, we attempted to address McHarg's critique by comparing suitability data to value-laden governance actions. While we do not argue that our approach predicts future pro-environmental governance, it does provide foundational

Table 8 Comparison of five multivariate regression models, given as standardized regression coefficients of dependent variable pro-environmental governance index

	Model 1	Model 2	Model 3	Model 4	Reduced model
ARC status (yes = 1, no = 0)	**− 0.482*****	− 0.131	− 0.117	− 0.227	**− 0.317*****
Energy					
Roadways		0.210	0.257	0.059	
Energy grid		**0.379*****	**0.261*****	0.198	**0.390*****
Biophysical					
Forest quality			0.249	0.309	
Farmland quality			**0.330*****	0.413	**0.241*****
Streams			0.0478	− 0.097	
Groundwater			− 0.175	0.048	
Geology			**0.194*****	**0.251*****	0.146
GAP status			− 0.181	− 0.017	
State conservation lands			− 0.063	− 0.0634	
Social					
Population change				0.104	
Unemployment				− 0.045	
Education centers				0.140	
Education				0.000	
Industry dependence				**− 0.246*****	**− 0.262*****
R^2	0.23	0.42	0.55	0.60	0.55
F	19.69	15.26	6.81	5.00	14.82
df	65	63	56	51	61

Bold values indicate significance less than 0.01

***Significant at the 0.01 level

**Significant at the 0.05 level

*Significant at the 0.10 level

Table 9 Top 5 ARC counties for key pro-environmental suitability factors

Suitability score	Energy grid	Farmland quality	Industry dependence
Allegheny	**Allegheny**		**Allegheny**
			Beaver
	Blair		
	Carbon		Carbon
		Clinton	
Greene		**Greene**	
Indiana	**Indiana**		
			Lackawanna
			Luzerne
Monroe			
		Pike	
		Potter	
		Sullivan	
Washington	**Washington**		

Bold text indicates counties with the top 5 highest suitablity scores

information toward developing design and planning strategies with respect to the unique socio-ecological conditions throughout the region.

For example, while difficult to organize and implement in a commonwealth, county-level policies may yield opportunities at the scale necessary to address the state's solar energy goals. Our analysis suggests investing in counties with the following four guiding criteria: (1) a growing population, (2) the capacity for educational centers offering job training programs, such as community colleges and technical schools, (3) a strong supporting local infrastructure of roads and transmission utilities, and (4) willingness to sacrifice non-prime forestlands. This is a bold and difficult argument to make in a state that values its forest-based recreation and related ecosystem services. Fortunately, our analysis supports that there is no need to infringe upon existing federal, state, or otherwise ecologically conserved areas or high-quality farmlands. There is ample space available to preserve the highest quality areas and meet the state's solar energy goals.

Ideally such criteria would be found in counties traditionally dependent on natural resource industries. However, advancing policies requires a critical mass of support from actors and agencies that drive governance actions. Our

analysis suggested that these areas will face the greatest difficulty in massing such support, as industry dependence was strongly correlated with lower levels of pro-environmental governance. Simply, the areas that have traditionally relied on natural resources, and are in the direst need of transition as the primary source of their livelihoods has steadily declined, are the *least* likely to support candidates with pro-environmental platforms. This contradicting narrative is endemic to the Appalachian Mountain Region and is the same conflict between physical and social environments that McHarg and Balint caution planners and designs about. Theoretically, the relationship between a person and their environment should influence their behavior (Ajzen 1991; Lewin 1935), especially in the cases of energy-based behaviors (Mainzer and Luloff 2017), barring perceived barriers. Wilkinson (1991, p. 7) describes one such barrier as the dynamic between physical and moral density. When physical density is low, people face challenges to forming strong bonds and the capacity for community agency. It may be that the spatial allocation of the region's built and natural resources is preventing the development of community-level bonds necessary to activate pro-environmental actions that yield governance networks targeting public policies. As a result, rural areas face challenges in developing communities (Wilkinson 1991, p. 7) and quality of life (Wilkinson 1991, p. 9).

We acknowledge that our analysis omits two key variables that were not feasible to include within the scope of our study: parcel availability and assessed value. Data quality, availability, and cost vary by county and would require a substantial effort to coordinate relative to the other datasets that was beyond the scope of our study. Perhaps for these reasons, we did not find evidence that either factor is typically included in solar suitability analysis beyond broad land use data. Yet these factors are important to consider in the future because they may dramatically influence the availability of suitable areas for infrastructure implementation. Broadly, urbanized areas contain a higher density of small parcel properties that are typically assessed at higher per acre value than found in rural areas. For example, while we identified 995 square miles of moderately suitable area in the Appalachian Mountain Region, we were unable to discount how much of that area is currently developed. Small parcel sizes, complex ownership, and the potentially high cost of acquiring land will be a major challenge to utility-scale solar infrastructure projects. We imagine two alternatives: that, despite our initial analysis, the moderately suitable areas identified in the Appalachian Mountain Region are much more suitable due to their assumed low acquisition cost compared to urbanized areas, such as Allegheny county; or that the future of solar infrastructure in Pennsylvania is not only utility-scale solar, but it is in small-scale implementation projects that interact with the existing built environment

of houses, commercial and office buildings, and roadway medians.

However, as the discussion of meeting Pennsylvania's solar goals evolves, we put forth that our model is a valid tool for identifying potential areas at the county level for investing in pro-environmental policies but one that needs further refinement. At the county scale, our analysis contains a relatively small number of data points and makes broad claims about internally diverse areas. Future efforts may need to explore aggregating data at the county subdivision (town) or census tract level. Further it is our ultimate goal to support strategies for transition for the entire multi-state Appalachian Mountain Region across multiple modes of renewable energy resources. While much of Pennsylvania is in a transitional status (ARC 2019), adjacent states contain predominantly distressed areas in greater need of transition. The scope of such a study is an order of magnitude larger than our current efforts, but it remains one that we hope our team and others will pursue based on the foundations identified in this pilot study.

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Stephen P. Mainzer explores the decision dynamics of coupled human and natural environments through socio-ecological systems approaches. He employs geospatial, statistical, and qualitative techniques to study ways in which the biophysical landscape—urban form, physiography, and ecology—intersects with pro-environmental energy behaviors and governance to inform evidence-based design and planning strategies.

C. A. Cole is the director of E+D: Ecology Plus Design. E+D is intended to blend ecological research with design to improve the function of what we place on the ground.

Travis Flohr focuses on green infrastructure and ecosystem service solutions to create healthy, vibrant, and resilient landscapes. His work relies on geospatial techniques to evaluate landscapes and conducts policy analysis on twenty-first-century landscape issues, promoting firewise and pollinator-friendly communities. His research interest includes: hazard resilient communities, spatial analysis, and environmental justice.