Constructing statutory energy goal compliant wind and solar PV infrastructure pathways [*]

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Abstract

Concerns over climate change have led governments around the world to establish a range of renewable, low-carbon energy goals. Plans for meeting these targets vary widely in their ambition, specificity, and time horizons. Wind and solar electricity generation will feature prominently in future energy systems that meet these renewable, low-carbon energy goals. Implementing large-scale wind and solar PV infrastructure configurations in a timely fashion will require cooperation between and among electric grid stakeholders and communities that host the infrastructure.

This paper presents methods for constructing a diverse range of wind and solar PV energy infrastructure pathways that meet statutory energy goals, measuring their land use impacts, and assessing their performance relative to electricity demand. A case study on the state of Vermont's statutory energy goals from its 2016 Comprehensive Energy Plan is presented as an example. While total wind and solar PV infrastructure requirements would increase several-fold, Vermont's statutory energy goals can be met while occupying less than 1% of the state's land area. Vermont electricity demand was most effectively met by balanced configurations of wind and solar PV similar to the state's present wind and solar PV resources, while 100% wind or 100% solar PV configurations were less effective.

Keywords

Electric grid; decarbonization; statutory energy goals; wind turbines; solar PV panels; land use.

Contents

1 Introduction

Climate change, driven by anthropogenic greenhouse gas emissions, has already increased global average surface temperatures by 1.0 °C [1]. The Intergovernmental Panel on Climate Change (IPCC) recently reiterated the need for "rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems" to limit global warming to 1.5 °C and avert the worst impacts of climate change [1]. Renewable, low-carbon energy sources, particularly wind and solar photovoltaic (PV) electricity generation, are increasingly being adopted worldwide both for environmental reasons and because of their increasingly competitive economic positions [2]. In response to these trends, local, regional, national, and international governments are establishing binding targets for renewable, low-carbon energy production, hereafter referred to as 'statutory energy goals' or SEGs [3] [4] [5]. Many SEGs focus on decarbonizing the electricity system and substituting fossil fuel energy consumption (e.g. transportation, heating, cooking, etc.) for electricity consumption. Achieving these SEGs through "rapid and far-reaching transitions" in the electricity system, among others, is crucial for averting the worst consequences of climate change.

Numerous studies of electricity systems powered by significant proportions of renewable, low-carbon energy sources have been conducted in recent years, covering topics including wind and solar PV generation reliability, electric grid stability and capacity constraints, and economic feasibility [6] [7] [8] [9] [10] [11] [12] [13]. These studies vary widely in their target wind and solar PV energy penetrations, the quantity and diversity of wind and solar PV infrastructure deployment scenarios tested, and the sophistication of their infrastructure siting methods. Relatively few studies explicitly consider the land use impacts of large-scale wind and solar PV infrastructure deployments and the influence of generation infrastructure siting choices on overall electricity system performance [14] [15] [16]. We contend that explicitly capturing these geospatial impacts of wind and solar PV electricity generation deployment is vital for understanding how high wind and solar PV-penetration electric grids will be implemented.

Large incumbent electricity generators like coal, natural gas, nuclear, and hydropower generate large quantities of electricity on relatively small, widely separated parcels of land. This dynamic leads to significant land use and related environmental landscape impacts in the few areas that host the generators themselves, leaving most other areas of the landscape essentially unaffected. A future wind and solar PV powered grid will likely draw energy from electricity generation infrastructure that is distributed much more widely across the landscape than incumbent generators thanks to their reliance on prevailing weather conditions for electricity generation and their inherent modularity [17] [18]. In turn, the infrastructure siting processes that attend electricity system decarbonization driven by wind and solar PV will not only rise sharply in number but will also frequently trigger opposition from those who oppose the landscape disruption that wind and solar PV can cause [19] [20]. Existing land uses, land protections, and unsuitable terrain like waterways and steep slopes will also constrain wind and solar PV deployment. These phenomena represent significant hurdles to wind and solar PV growth and, if not recognized and dealt with, could greatly hinder the implementation of decarbonized electricity systems mandated by SEGs both in time and in scope. In North America, regional transmission organizations (RTOs) and independent system operators (ISOs) are charged with operating and modernizing the electric grid. RTOs and ISOs are under pressure to both accommodate new wind and solar PV generation capacity and maintain existing grid safety and energy provision reliability standards. If RTOs and ISOs can proactively plan for grid extensions and upgrades to accommodate high penetrations of wind and solar PV generation infrastructure, the chances of SEG achievement and continued grid reliability will increase dramatically. More granular infrastructure siting and landscape impact information can therefore enhance the efficacy of grid planning exercises and contribute significantly to grid decarbonization efforts.

This paper examines how different SEG-compatible wind and solar PV configurations compare on the basis of total generation infrastructure needs, land use requirements, and electricity demand satisfaction. The model used to build SEG-compatible wind and solar PV configurations relies on five years of high spatiotemporal resolution weather data for the continental United States (CONUS) to provide granular, high-quality electricity generation estimates. A case study for the

American state of Vermont and its SEGs is presented to illustrate how different wind and solar PV infrastructure ratios, siting patterns, and electricity demand levels drive wind and solar PV electricity generation infrastructure needs. By better defining what SEG-compatible wind and solar PV deployments look like and what impacts they have on the landscape, grid integration and planning studies can more readily capture the operational dynamics of highly wind and solar PV dependent electrical systems and reckon with the implementation challenges that will shape real-world, large-scale grid decarbonization. Section 2 of this paper describes the datasets and modeling methods used to produce SEG-compatible wind and solar PV infrastructure deployments. Section 3 establishes the Vermont case study and section 4 contains the results of the case study scenarios. Section 5 contains a discussion of the case study findings and context for the enhancement and application of this study. Section 6 provides a concluding summary of this paper and suggested areas for proceeding work.

2 Methods and Data

The Renewable Energy Growth Scenario (REGS) model described here is an evolution of the model presented in [8]. Our model uses higher spatial resolution wind speed and sunlight data, two types of solar PV panels, and incorporates existing wind and solar PV generation infrastructure. Like [8], our model covers all of CONUS and allows for discrete modeling of wind and solar PV infrastructure by sub-region. Unlike [8], our model does not consider offshore wind turbine siting.

2.1 Weather data

[21] provides hourly irradiance and 80m elevation wind speed data from 2013 to 2017 for the CONUS, southern Canada, and northern Mexico on a 3km by 3km grid. The REGS model uses 43,800 hours of data spanning 0800 UTC 1 January 2013 to 0700 UTC 1 January 2018. 29 February 2016 is omitted to simplify year-to-year comparisons and daylight saving time is ignored. Of the 43,800 hours possible in this date range, the JDS contains 35,192 hourly files for an availability rate of 80.3%. Gaps in the data were filled by systematically copying available data from equivalent hours in other years to ensure that climatological characteristics and sunlight availability are identical. The JDS was created using an experimental version of the High Resolution Rapid Refresh numerical weather prediction model. Biases in the wind and solar data are noted in sections 2.3, 2.4, and 5 of [21]. Wind speed biases in the JDS data are modest at approximately 0.5 to 1 m/s higher than observed wind speeds at a test site in Colorado. Sunlight biases are shown to be more variable across CONUS. In New England, where this paper's case study is located, sunlight biases in the JDS are as much as 0.75 kWh m^{-2} day^{-1} sunnier than observations. See section 3.5 for further discussion.

2.2 Wind and solar PV power generation

Wind and solar PV electricity generation estimates are calculated using the JDS and a variety of assumptions about wind turbines and solar PV panels. This paper assumes that all installed wind and solar PV infrastructure remains perfectly operational at all times and generates power purely as determined by the prevailing weather conditions. We do not attempt to account for infrastructure outages or performance degradation such as solar PV panel soiling, solar PV cell degradation, wind turbine equipment maintenance, wind turbine icing curtailment, electric grid connectivity interruptions, and so on. Additionally, all new wind and solar PV infrastructure placements are assumed to be accomplished with existing, commonly available turbines and PV panels.

2.2.1 Wind turbine modeling

All wind turbines (existing and new) are assumed to have hub heights of 80m, matching the elevation of wind speed data provided by the JDS. Hourly wind power capacity factors are calculated as a fraction of nameplate capacity using the following generic wind turbine power curve equation:

$$CF_{wind} = 0.52 * \tanh[(0.34 * W_{80m}) - 2.6] + 0.48 \tag{1}$$

for all wind speeds between 3 m/s and 15 m/s, where W_{80m} is the 80m wind speed from the JDS (see figure 1). Wind speeds between 15 m/s and 25 m/s result in $CF_{wind} = 1$; wind speeds lower than 3 m/s or higher than 25 m/s result in $CF_{wind} = 0$. This wind turbine power curve approximates the wind turbine power curve presented in [22].

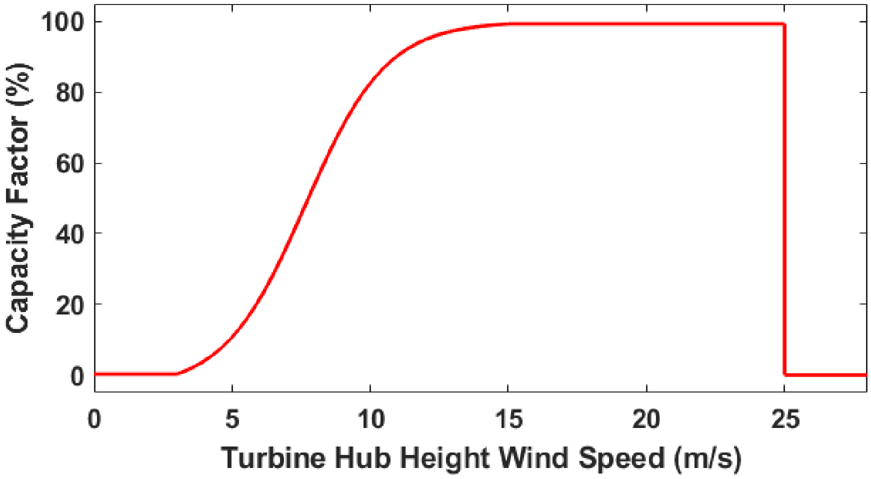

Figure 1: Wind turbine power generation curve

2.2.2 Solar PV panel modeling

Hourly solar PV panel capacity factors are calculated as a fraction of nameplate capacity using information about the solar PV panel mounting type, mounting location, and orientation relative to the Sun. All solar PV infrastructure is assumed to be either fixed-angle solar PV (FAPV) panels or two-axis tracking solar PV (TPV) panels. The orientation of a solar PV panel along with its latitude, longitude, and local time zone (i.e. hours offset from Greenwich Mean Time) are used to calculate θ, the angle between the Sun's rays and the solar PV panel's normal vector at a given hour. All TPV panels are assumed to track the Sun perfectly and therefore have $\theta = 0^\circ$ at all times. θ values for FAPV panels are calculated using [23]'s method as follows:

$$\theta = \arccos\Big\{(A - B)\sin\delta + [C\sin\delta + (D + E)\cos\omega]\Big\} \tag{2}$$

where:

$$A = \sin\phi\cos\beta \tag{3}$$

$$B = \cos\phi\sin\beta\cos\gamma \tag{4}$$

$$C = \sin\beta\sin\gamma \tag{5}$$

$$D = \cos\phi\cos\beta \tag{6}$$

$$E = \sin\phi\sin\beta\cos\gamma \tag{7}$$

and:

$$\beta = \text{PV panel tilt angle} \tag{8}$$

$$\gamma = \text{PV panel rotation angle} \tag{9}$$

$$\delta = 23.45 * \sin\left[\frac{360 * (284 + JD)}{365}\right] \tag{10}$$

$$\phi = \text{latitude} \tag{11}$$

$$\psi = \text{longitude} \tag{12}$$

$$\omega = 15(TZ - 12) + [(15 * LT) - (15 * TZ)] + [(15 * TZ) - \psi] \tag{13}$$

$$JD = \text{Julian day} \tag{14}$$

$$LT = \text{Local Time (hours)} \tag{15}$$

$$TZ = \text{Time Zone (hours offset from Greenwich Mean Time)} \tag{16}$$

Sunlight data from the JDS are provided as sunlight fluxes normal to Earth's surface. Deriving the capacity factor of an inclined solar PV panel of either type therefore requires the calculation of R_b, the ratio of sunlight exposure on an inclined surface to the sunlight exposure on a horizontal surface. Using [24]'s method, R_b is calculated as follows:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{17}$$

where:

$$\cos\theta_z = \cos\phi\sin\delta + \cos\phi\cos\omega\cos\delta \tag{18}$$

For overnight hours, R_b is set to zero. R_b is capped at 4 to limit artificial overproduction of solar power in hours very near sunrise and sunset. R_b is then used to calculate solar panel capacity factors, CF_{PV}, as follows:

$$CF_{PV} = \begin{cases} S_{JDS} * R_b & S_{JDS} \leq S_{CS} \\ S_{CS} * R_b & S_{JDS} > S_{CS} \end{cases} \tag{19}$$

where S_{JDS} is the solar irradiance at the surface in W/m^2 from the JDS and S_{CS} is the estimated horizontal clear sky solar irradiance at the surface using [25]'s method:

$$S_{CS} = 1098 * \cos\theta_z * \exp\left\{\frac{-0.057}{\cos\theta_z}\right\} \tag{20}$$

2.2.3 Conversion of capacity factors to power generation

Wind and solar PV power generation per hour per JDS grid box is calculated by multiplying the nameplate capacities of each type of generator with their respective capacity factor data. Wind turbines are assumed to generate alternating current (AC) power matching their nameplate capacities. Solar PV panels are assumed to produce direct current (DC) power at their nameplate capacities; AC power generation is determined by factoring in user-defined inverter losses.

CF_{wind} and CF_{PV} are linearly interpolated on a minutely basis to reduce power generation errors. If CF_{wind} and CF_{PV} were used to calculate hourly generation directly, only the weather conditions at the start of the hour would determine generation for the entire hour. For example, if a given location experiences calm winds at the start of an hour and strong winds at the start of the next hour, the entire intervening hour would have no wind power generation. Similarly, hours in which the Sun rises would erroneously have no solar PV power generation for the entire hour and hours in which the Sun sets would erroneously generate solar PV power after sunset. By interpolating generation between hours on a minutely basis, the general trends of the wind and sun resources intra-hour are captured, though some variability is undoubtedly missing as compared to the real-world meteorological conditions. Capturing this variability would require higher time resolution data which is not yet available.

2.3 Wind and solar PV land use

The REGS model aggregates wind and solar PV infrastructure land use to 3km by 3km grid boxes matching those of the JDS. Existing wind and solar PV infrastructure, if provided, is first aggregated to the nearest grid box and then parameterized at a fixed rate of nameplate capacity per m^2. All subsequent wind and solar PV infrastructure is added in 60m by 60m (3600 m^2) increments.

All FAPV infrastructure is assumed to occupy land at a rate of 186 kW_{DC} per 60m by 60m plot (51.67 W_{DC} per m^2) and all TPV infrastructure is assumed to occupy land at a rate of 96 kW_{DC} per 60m by 60m plot (26.67 W_{DC} per m^2). FAPV land use intensity is drawn directly from [26], while TPV use land intensity is slightly lower than the value reported in [26] based on estimates of existing TPV facilities in the state of Vermont. Rooftop FAPV installations are treated as if they are ground-mounted and therefore occupy land.

All wind turbines are assumed to occupy land at a rate of 3,000 kW_{AC} per 60m by 60m plot (83.33 W_{AC} per m^2). All new and existing wind turbines, regardless of nameplate capacity, are assumed to have an 80m hub height to simplify capacity factor calculations. To prevent wind turbine overcrowding[1], total wind turbine capacity is capped at 27 MW_{AC} per grid box, equivalent to nine, 3MW_{AC} wind turbines per grid box or 3MW_{AC} per km^2. Additional direct land use impacts of wind turbines such as service roads, easements, electricity transformation and transmission infrastructure, service buildings, meteorological observation equipment, etc. are not included in this model. While these attendant secondary land use impacts are typically much larger than the footprint of a wind turbine itself, it is difficult to accurately and fairly parameterize these land use impacts given the variability in wind farm configurations [27].

2.4 Modeling methods

The REGS model constructs new wind and solar PV infrastructure configurations by using weighted random number selection to determine the infrastructure type, infrastructure siting method, and finally the location of the new wind turbine or solar PV panel array within the desired domain. The model is intialized with parameters indicating which grid boxes within CONUS are included in the test domain, how much land within each test domain grid box is restricted for development, where existing wind and solar PV infrastructure exists in the test domain, the desired ratio of new FAPV nameplate capacity to new TPV nameplate capacity to new wind turbine nameplate capacity, the desired infrastructure siting methodologies and their relative frequency, and the desired modeling goal (e.g. a specific amount of total wind and solar

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[1] Wind turbines cannot be placed directly next to one another as solar PV panels can due to the inherent spacing required between wind turbines to maintain operational safety and downwind wake effects on neighboring wind turbines. This spacing is referred to in this work as *indirect land use*. The modeling restriction of 9 wind turbines per 9km^2 imposed here thus means that indirect land use is incurred at a rate of 1/3 km^2 per MW_{AC} of wind turbine capacity.

PV nameplate capacity, land occupation, or TWh of annual electricity generation). Parameters that weight infrastructure type and infrastructure siting method to the user's specifications are also included.

New wind and solar PV infrastructure placements are performed individually in an iterative process. Figure 2 provides a visual flowchart summary of the REGS model infrastructure siting process. First, infrastructure type is selected randomly based on the user-defined ratio of desired new infrastructure types. As the model runs, infrastructure types that are over-represented as a percentage of newly installed capacity in the model are excluded from selection. As subsequent infrastructure selections are made, the relative proportion of a particular infrastructure type recedes towards the desired ratio until ultimately it is under-represented and is made eligible for selection. This "rubber-banding" effect prevents the final infrastructure ratio from diverging substantially from the user's desired infrastructure ratio. In cases where the model is tasked to maximize electricity generation over other factors, this model behavior also gives each infrastructure type a proportionally fair chance to occupy the highest average electricity generation locations, particularly when grid boxes have both a high quality wind and sunlight resource. Once the infrastructure type is selected, one of three infrastructure siting methods is chosen. New infrastructure can be placed to maximize electricity generation, to occupy grid boxes where other infrastructure of its own type is already located (hereafter referred to as *clustering*), and randomly. Finally, the model randomly selects the grid box which will receive the new infrastructure placement, subject to existing direct and indirect land use occupation, land use restrictions, and user-defined siting preferences. The probability of a given grid box receiving the new infrastructure placement depends on the siting criteria selected and how much bias is given towards high quality grid boxes versus low quality grid boxes. If a new wind turbine is being placed to maximize generation, for example, the model scales the estimated annual TWh generation of each grid box in the domain by a user-defined exponent. Next, the cumulative sum of these values is calculated and site selection probabilities for each grid box are assigned based on the grid box's share of the cumulative sum. Finally, a random number draw determines which eligible grid box receives the new wind turbine or solar PV panel array. The additional land use incurred and electricity generated by the new infrastructure is added to the existing wind and solar PV infrastructure, thus completing the cycle. If the most recent infrastructure placement does not break the target modeling threshold, the model begins the infrastructure placement process anew. Otherwise, the model reports out the locations and amounts of new wind and solar PV infrastructure deployed by the model.

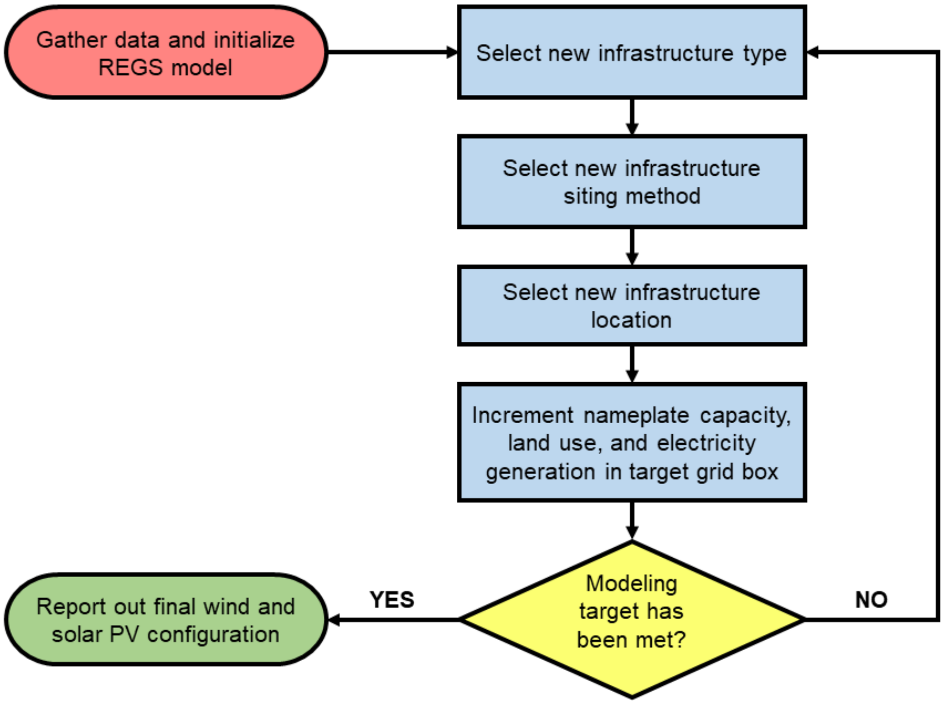

Figure 2: REGS model flowchart

3 Vermont Case Study

The remainder of this paper uses the REGS model to perform a case study of the state of Vermont and its SEGs. This case study aims to illustrate how different wind and solar PV infrastructure choices can be used to meet SEGs, how different wind and solar PV siting strategies can influence electricity generation returns, and the land use consequences of these choices.

3.1 Current statutory energy goals

Vermont has established several SEGs that govern electricity, heating/cooling, transportation, and other energy uses. These SEGs are catalogued in the state's 2016 Comprehensive Energy Plan (CEP) [4]. The 2016 CEP establishes goals of meeting 90% of Vermont's total energy needs with renewable energy sources by 2050, with intermediate goals of 40% by 2035 and 25% by 2025. Additional sector-specific goals relevant to the present study include meeting 67% of electricity demand by 2025 and 75% of electricity demand by 2032 with renewable energy sources, meeting 25% of total energy demand with in-state renewable energy resources by 2025, and meeting 10% of electricity demand from distributed generation resources (e.g. rooftop solar PV, small-scale wind turbines, waste-to-energy systems, etc.) by 2032. Though this case study focuses on SEGs related to the electricity sector, it is likely that some fraction of presently non-electric energy consumption in Vermont and elsewhere will be electrified even under business-as-usual conditions. This study will therefore consider, in general terms, the potential increase in electricity demand in Vermont from increased electrification of non-electric energy demands. More generally, the 2016 CEP reiterates the state's long-term goal of limiting Vermont's overall greenhouse gas emissions in 2050 to 25% of the state's 1990 greenhouse gas emissions. Meeting this goal will likely require significant electrification of presently non-electric energy demands and, consequently, significant growth in the generation of low-carbon or carbonless electricity to meet these new energy demands.

3.2 Wind and sunlight resources

The state of Vermont is relatively small compared to other American states in terms of land area, population, and total energy consumption [28]. Significant portions of Vermont are covered by lakes, wetlands, and a variety of protected lands managed by local, state, and federal agencies. The majority of Vermont's protected lands lie along the Green Mountains and adjacent foothills which run north-south through the center of Vermont (see figures 3A and 3B). The Green Mountains also significantly influence Vermont's wind and sunlight resource quality. The western slopes and peaks of the Green Mountains are home to Vermont's highest mean wind speeds as indicated by the dark green stripe in eastern Chittenden, Addison, Rutland, and Bennington counties (see figure 3C). The lowest mean wind speeds in Vermont are found in the valleys immediately east (climatologically downwind) of the Green Mountains in Lamoille, Washington, and western Orange Counties as well as the broader Connecticut River valley along the eastern edge of Vermont. In figure 3D, the impact of the climatological rain shadow induced by the Green Mountains can be clearly seen. Areas east of the Green Mountains, particularly Windsor and Windham counties, are 10 to 30% sunnier than western Vermont. Mean solar irradiance is much less variable than mean wind speeds across the Vermont, however, with the windiest locations in Vermont having almost triple the mean wind speed of the calmest locations. Wind turbine electricity generation potential is therefore much more sensitive to siting than solar PV generation in Vermont.

3.3 Existing wind and solar PV infrastructure

At the beginning of 2018, Vermont had approximately 149 MW_{AC} of wind turbines, 168 MW_{DC} of FAPV, and 19 MW_{DC} of TPV [32] (see figure 4). The ratio of FAPV to TPV to wind turbine nameplate capacity in Vermont is thus 444 kW_{AC} to 56 kW_{DC} to 500 kW_{DC} per MW of total nameplate capacity. Rooftop FAPV capacity represents 58 MW_{DC} (34.4%) of the total FAPV capacity. Vermont's five active wind farms are located on or near mountain peaks, far from large populations centers.

Vermont covers a total of 25,146 km^2, of which 18,305 km^2 [72.8%] is not covered

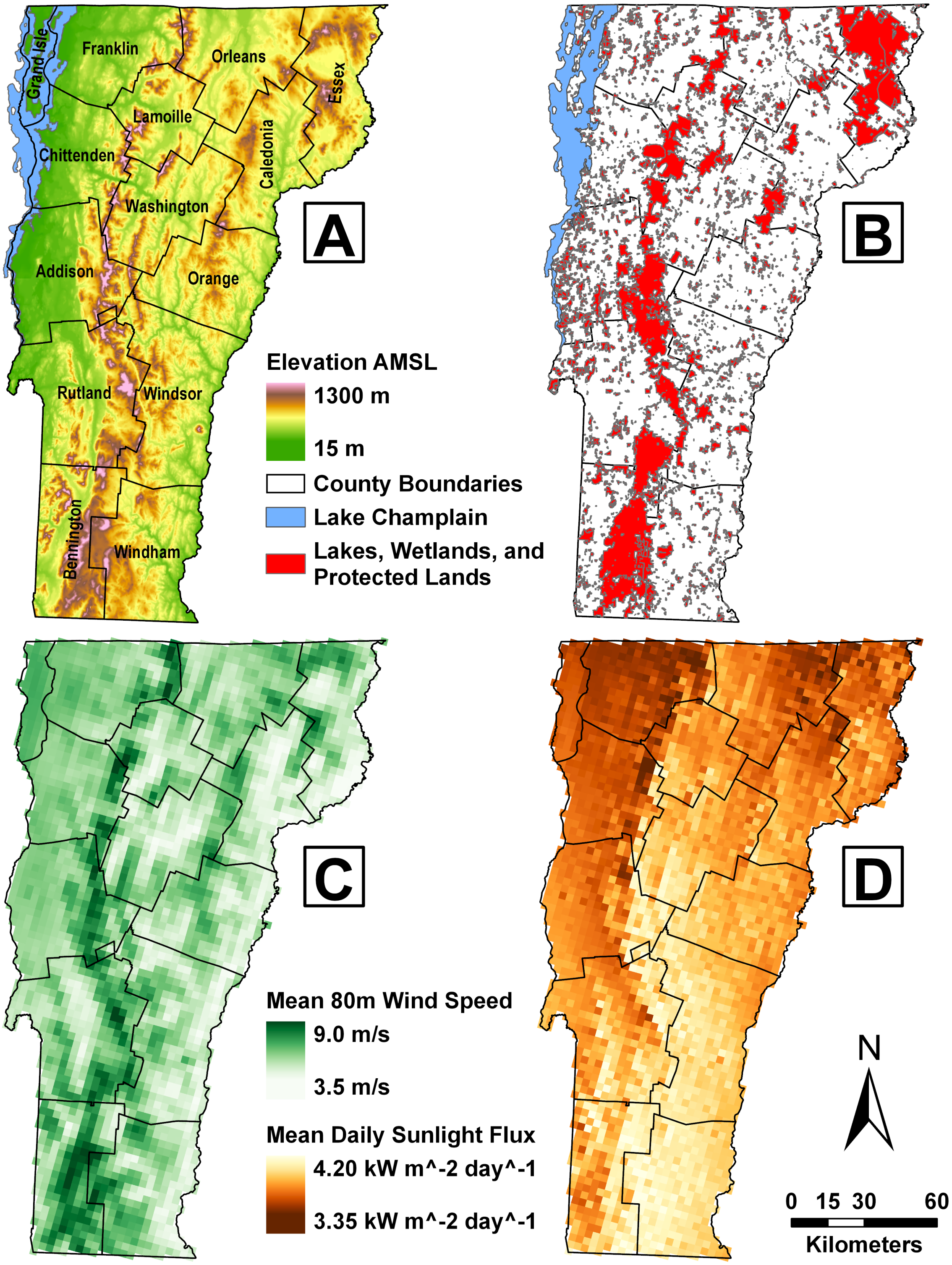

Figure 3: (A) Elevation above mean sea level, county names, and county boundaries [29]
(B) Lakes, wetlands, and protected lands [30] [31]
(C) Mean wind speed at wind turbine hub height [21]
(D) Mean daily solar irradiance at Earth's surface [21].

by surface water, wetlands, conservation and wildlife protections, or is otherwise restricted from development. Existing wind and solar PV infrastructure covers approximately 4.14 km^2 [0.017%] of Vermont[2]. Much of Vermont's solar PV capacity is located in and around the state's largest towns and cities, such as Burlington (Chittenden County), Middlebury (Addison County), Montpelier (Washington County), and Brattleboro (Windham County). Table 1 summarizes the distribution of solar PV generation capacity across Vermont's 14 counties and the size of each county. All Vermont counties have at least some installed solar PV capacity. Chittenden and Addison counties alone provide over a third of Vermont's solar PV capacity despite having only 15% of Vermont's land area.

	Total Area (sq. km)	Total Area (% of VT)	Available Area (sq. km)	Available Area (% of VT)	Solar PV Capacity (MW$_{DC}$)	Solar PV Capacity (% of VT)
Addison	2,114	8.41	1,276	6.97	31.055	16.55
Bennington	1,766	7.02	971	5.30	8.011	4.27
Caledonia	1,722	6.85	1,462	7.99	5.552	2.96
Chittenden	1,623	6.45	1,121	6.13	40.378	21.53
Essex	1,766	7.02	857	4.68	1.193	0.64
Franklin	1,817	7.22	1,374	7.51	14.056	7.50
Grand Isle	510	2.03	177	0.97	2.680	1.43
Lamoille	1,214	4.83	902	4.93	6.152	3.28
Orange	1,809	7.19	1,653	9.03	12.712	6.78
Orleans	1,889	7.51	1,547	8.45	7.075	3.77
Rutland	2,466	9.81	1,759	9.61	19.922	10.62
Washington	1,821	7.24	1,451	7.92	13.241	7.06
Windham	2,080	8.27	1,669	9.12	9.395	5.01
Windsor	2,548	10.13	2,086	11.39	16.102	8.59
TOTAL	25,146		18,305		187.504	

Table 1: Vermont land area and January 2018 solar PV infrastructure

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[2] 4.14 km^2 of land use assumes rooftop solar PV panels are instead ground-mounted as laid out in section 2.3. This and other land use estimates made in this paper therefore represent a likely 'worst-case scenario' upper bound or overestimate of actual solar PV land use.

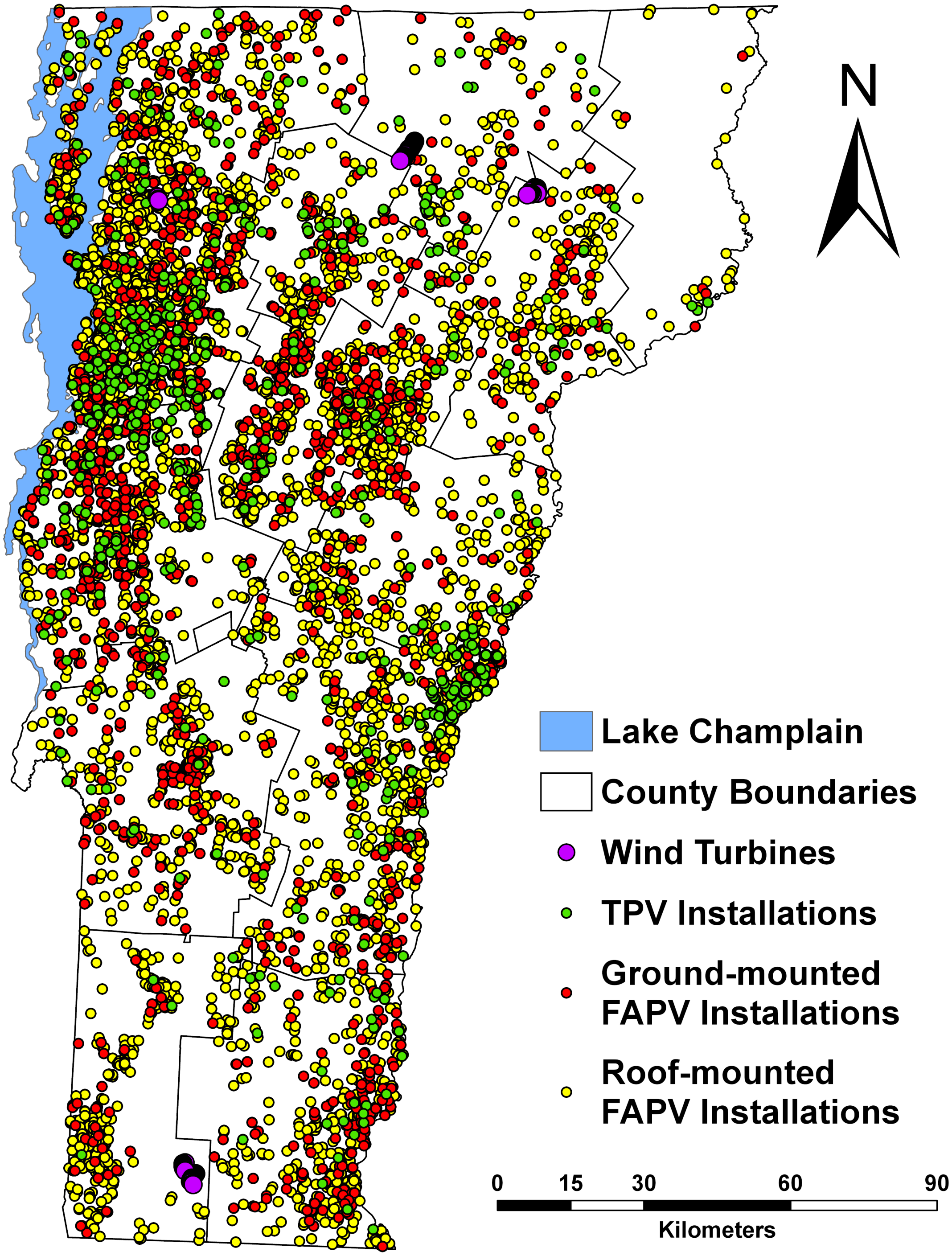

Figure 4: Estimated installed wind turbines and solar PV panels in Vermont as of January 2018. Wind turbines are marked individually and solar PV panels are grouped by installation and then marked. For the sake of map readability, dot size does not reflect installed generation capacity.

3.4 Annual electricity imports, in-state generation, and consumption

Vermont relies on a range of in-state and out-of-state electricity generation capacity to meet its electricity needs. Of the 5.522 TWh of electricity sales made in Vermont in 2018, 1.392 TWh (25.2%) were met by in-state hydroelectric generation, 0.421 TWh (7.6%) were met by in-state biomass generation, 0.393 TWh (7.1%) were met by in-state wind generation, and 0.273 TWh (4.9%) were met by in-state solar PV generation, resulting in a total of 2.479 TWh (44.9%) of electricity demand being met by renewable electricity generation sources[3] [33]. A further approximately 1.300 TWh (23.5%) of hydroelectric power is supplied to Vermont by Québec per year [4]. The remaining 1.743 TWh (31.6%) of electricity demand per year is met by a range of conventional generation sources (primarily coal, natural gas, hydroelectric, and nuclear) located across New England. Total energy consumption in Vermont in 2016 was 128.7 trillion British Thermal Units (BTU), equivalent to 37.718 TWh of electrical energy [34]. Assuming a similar amount of total energy was consumed in 2018, electricity therefore represented just 14.64% of Vermont's total energy demand in 2018 (not including losses and inefficiencies in electricity generation, transmission, and distribution), resulting in wind and solar PV generation resources within Vermont meeting only 1.76% of Vermont's total energy demand in 2018.

Total annual electricity demand is only one measure of electricity system performance, however; the hour-by-hour fluctuations in electricity demand determine which generators (and therefore which fuels) are used by grid operators to meet electricity demand. Figure 5 shows mean hourly Vermont electricity demand (hereafter referred to as *load*) for the years 2013-2017, corresponding to each hour of weather data from the JDS [35]. Vermont load exhibits diurnal and seasonal patterns in-line with other developed societies in temperate climates. Load at any given time is influenced by the prevailing weather conditions in a given region (particularly temperature), time of day, day of the week, holidays, and normal electricity consumer behaviors. Grid operators obey a "supply follows demand" paradigm which means they must ramp generators up and down as

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[3] The REGS model estimates that Vermont's January 2018 wind and solar PV infrastructure would have generated an average of 0.366 TWh of wind power per year and 0.275 TWh of solar PV power per year when parameterized as discussed in sections 2.2.1, 2.2.2, and 3.5.

load increases and decreases. The sharp load increase between 4AM and 7AM and corresponding load decrease between 6PM and 10PM are particularly challenging for grid operators to manage. As controllable generation sources are replaced by intermittent generators like wind and solar PV, it will be increasingly difficult for grid operators to meet load reliably and safely. Measuring the effectiveness with which wind and solar PV meet load in the absence of large-scale energy storage device deployment or coordinated wind and solar PV generation curtailment is therefore an important metric to consider when analyzing large-scale wind and solar PV infrastructure deployments.

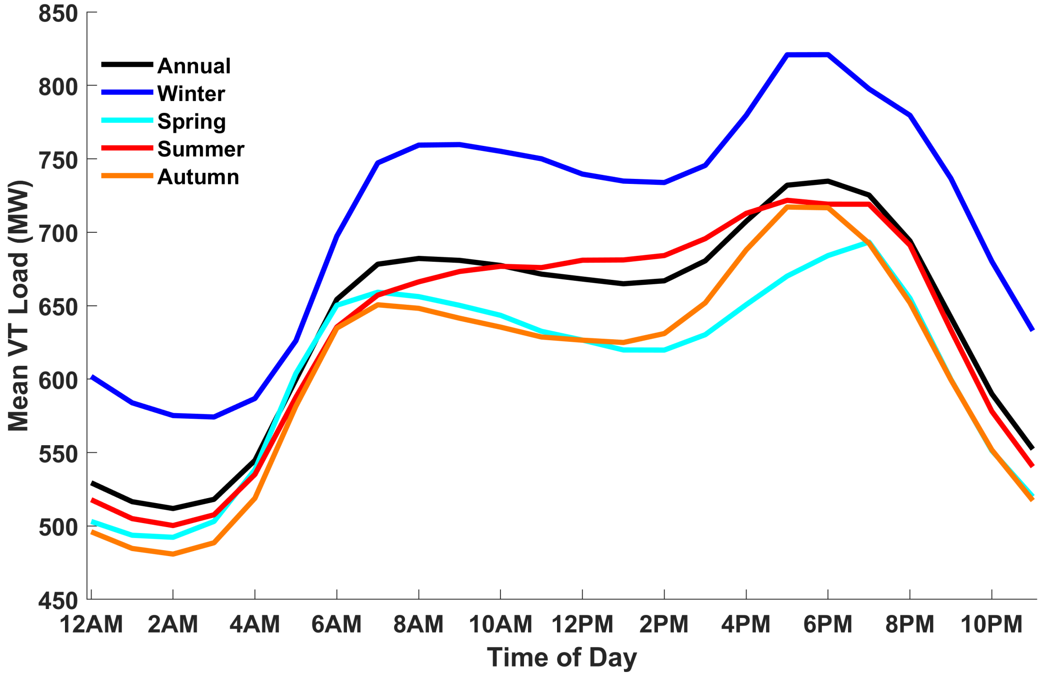

Figure 5: Average daily Vermont electricity demand for 2013 through 2017 [35]. Winter includes December, January, and February; spring includes March, April, and May; summer includes June, July, and August; autumn includes September, October, and November.

3.5 Modeling assumptions and parameters

This paper applies a number of modeling assumptions and parameterizations to the REGS in order to minimize the operational differences of real-world wind and solar PV infrastructure deployments to simulated configurations. The assumptions and parameters listed here are user-controllable options within the REGS model, rather than inherent modeling choices such as the assumption of an 80m turbine hub height for all existing and new wind turbines.

- Reduction of sunlight and wind biases (see section 2.1). The JDS carries biases in both wind and sunlight which must be counter-balanced in order to produce more realistic electricity generation data. For the below case study, wind speeds are unmodified while irradiance is reduced by 15%. While wind speeds in the JDS were verified against a sample wind turbine in the state of Colorado, it is not clear if the same biases are present in New England generally or Vermont specifically. Regardless, the modeled average annual wind power generation for Vermont's 149 $\mathrm{MW_{AC}}$ of wind turbines only slightly underestimates the actual reported Vermont wind power generation from 2018 (0.366 TWh versus 0.393 TWh, respectively). We therefore elect to leave the JDS' wind speed data unchanged. Irradiance data were reduced by 15% to offset the sunny bias present in the northeastern CONUS as depicted in figure 15 of [21].

- FAPV panel orientation. Solar PV panels are mounted at a wide variety of angles relative to the Sun and for a wide variety of reasons. While [32] provides basic information about the PV panel mounting type and mobility, the exact orientation of FAPV panels is not provided. In this case study, all FAPV panels are assumed to remain in one position year-round. Furthermore, all FAPV panels are assumed to be oriented equatorward (i.e. due south for all locations in the CONUS) and inclined at an angle of one half of local latitude. This orientation represents a more optimal panel orientation for summer solar PV generation potential and a balanced solar PV generation potential with respect to time of day [36].

- Power conversion losses. Both wind turbines and solar PV panels produce power which cannot be transmitted directly to the grid. Wind turbines typically generate power in AC but at a grid-asynchronous frequency. Solar PV panels produce DC power which can be used directly for local consumption (e.g. charging a battery or an electric vehicle) but must be converted to AC for transmission to the grid. In both cases, the power losses from the necessary conversion processes are small; for simplicity, this case study assumes they are zero. Inverters are typically built into wind turbines themselves and are therefore sized to match their nameplate capacities. Again, this case study assumes this to be the case and leaves wind turbine power generation unchanged. Solar PV panel arrays typically share inverters across panels given the small individual nameplate capacity of individual panels. The economics of inverters means that higher capacity and higher efficiency inverters are more expensive than lower capacity and lower efficiency inverters. Since solar PV panel arrays will rarely achieve their full rated power generation capacity, it is generally uneconomical to pair solar PV panel arrays with inverters of matching capacities [37]. This case study therefore applies a 20% reduction in AC solar PV power generation relative to DC solar PV power generation to account for this inverter sizing discrepancy.

4 Results

To illustrate how different SEG-compatible wind and solar PV configurations compare on total infrastructure needs, land use, and load satisfaction, a range of potential wind and solar PV configurations for the state of Vermont are developed and examined. First, we examine how Vermont's existing wind and solar PV infrastructure performs as compared to hypothetical alternative arrangements of the same amounts of infrastructure. Second, we construct and analyze a range of expanded wind and solar PV infrastructure deployments that satisfy four Vermont SEGs using ratios of wind and solar PV infrastructure that match the initial infrastructure deployment. Third, we construct SEG-compliant infrastructure configurations that extend the initial wind and solar PV configuration solely using wind turbines or solely using solar PV panels. Fourth, each of the above wind and solar PV infrastructure configurations is tested against real-world Vermont load data to assess its ability to meet load. These results, in combination, provide insights on the amounts of wind and solar PV infrastructure needed to satisfy SEGs and the general strengths and weaknesses of each as a potential pathway for renewable, low-carbon electricity provision in Vermont.

A combination of four SEGs, as described in [4], form the basis for future wind and solar PV infrastructure deployment targets analyzed in this paper. The four SEGs chosen for testing are:

- Meet 100% of Vermont's electricity demand with renewable energy sources
- Meet 25% of Vermont's total energy demand with renewable energy sources
- Meet 25% of Vermont's total energy demand with in-state renewable energy sources
- Meet 40% of Vermont's total energy demand with renewable energy sources

These targets correspond to approximately 5.5 TWh, 9.4 TWh, 9.4 TWh, and 15.1 TWh of electricity per year, respectively [34]. In order to set appropriate target levels of total new wind and solar PV electricity generation needed, existing renewable electricity generation detailed above (not including existing wind and solar PV generation) must be deducted. All 1.8 TWh of annual

Vermont renewable electricity generation not derived from wind or solar PV plus the 1.3 TWh of hydroelectricity imported annually from Québec can be deducted from the first, second, and fourth SEG targets. Only the approximately 1.8 TWh of in-state annual Vermont renewable electricity can be deducted from the third SEG target. The final annual wind and solar PV electricity generation targets to be examined are therefore 2.4 TWh, 6.3 TWh, 7.6 TWh, and 12.0 TWh. These scenarios represent approximate increases of wind and solar PV electricity generation in Vermont relative to January 2018 by a factor of 3.5, 9.5, 11.5, and 18, respectively. The nameplate capacity, land use, and electricity generation data reported in the proceeding tables and figures reflect the mean and standard deviation of 50 identically parameterized model runs. Differences between model runs arise from variations in random number selections that determine infrastructure type selection and site selection as discussed in section 2.4. Figures that depict wind and/or solar PV infrastructure deployments show only one representative result of the 50 total iterations.

4.1 Evaluating Vermont's current wind and solar PV infrastructure

As a first step towards building SEG-compatible wind and solar PV infrastructure configurations, we examine the electricity generation performance of Vermont's existing wind and solar PV infrastructure relative to two hypothetical infrastructure redeployments. The first alternative siting method strongly biases infrastructure placements of both types towards high annual electricity generation locations within the domain. This siting strategy, referred to hereafter as 'maximum generation', does not involve any optimization methodologies. The second alternative siting method is a simple random placement scheme and is referred to as such hereafter. This siting scheme acts as a control scenario for comparison against other siting methods and to the existing Vermont wind and solar PV configuration.

Figure 6 depicts example deployments of wind and solar PV under each alternative siting scheme relative to the status quo deployment. As expected, wind turbines are located along the spine of the Green Mountains in central Vermont under the maximum generation scenario. Solar PV panels are predominantly located in southern and eastern Vermont, matching the state’s strongest sunlight resource areas east of the Green Mountains. Both of the maximum generation scenario configurations differ sharply from the actual deployment of wind and solar PV infrastructure in Vermont. Most of Vermont’s existing wind turbines, while sited on locally high terrain, do not capture the state’s peak mean wind speeds. Likewise, much of Vermont’s best solar resource is only partially utilized at best by the present solar PV panel deployment. As is discussed in later sections of this paper, maximizing generation output is but one of many criteria that prospective developers must consider when selecting a plot of land for wind and solar PV energy infrastructure installation. Random placement of both wind turbines and solar PV panels creates infrastructure deployments that resemble neither the actual deployment nor the maximum generation scenario.

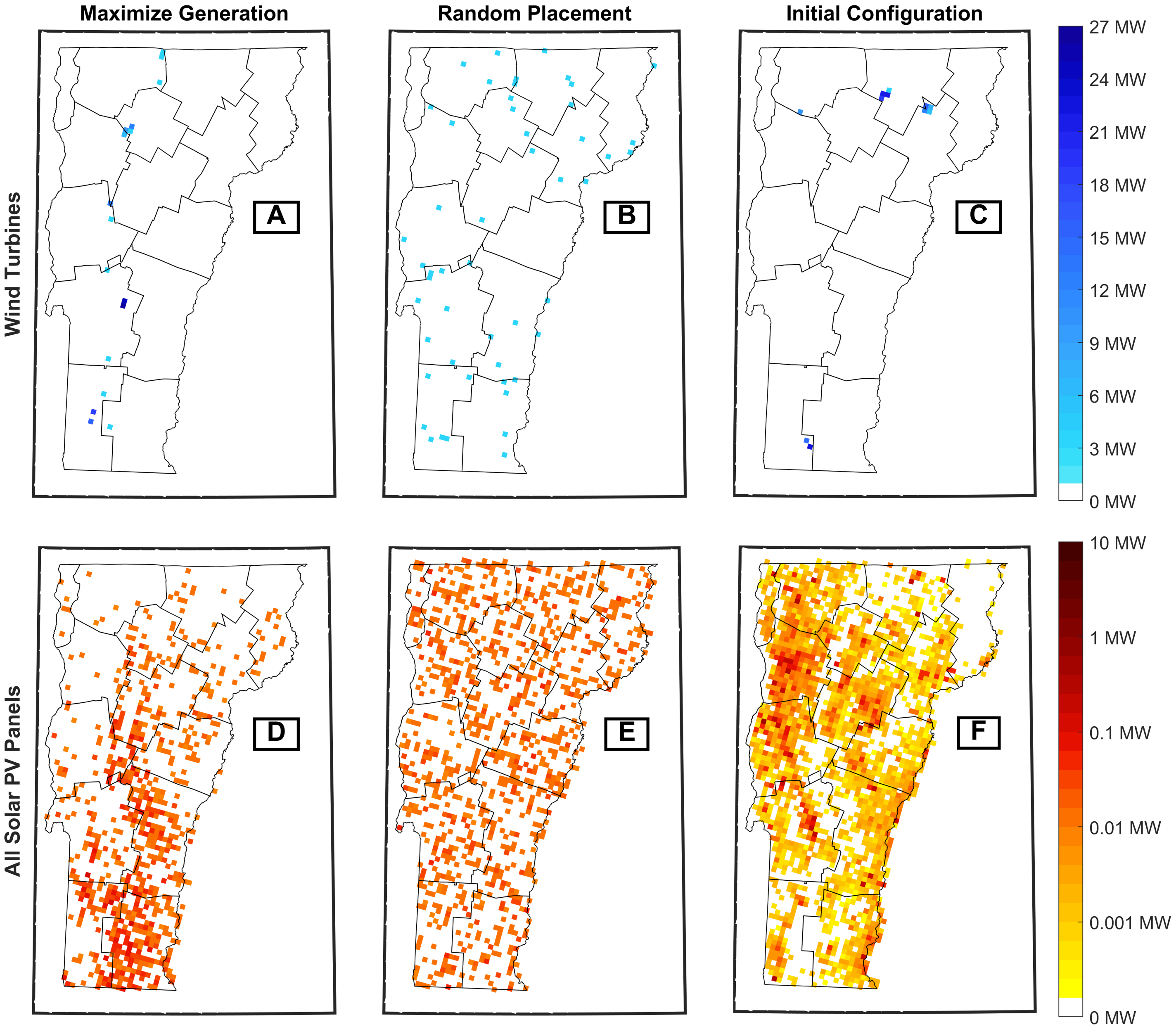

Figure 6: Actual and hypothetical alternative Vermont wind and solar PV infrastructure arrangements

Table 2 shows the corresponding mean annual electricity generation performance of the two alternative wind and solar PV infrastructure siting methods and of the initial Vermont wind and solar PV infrastructure configuration. As expected, the maximum generation siting methods produce infrastructure configurations that outperform Vermont's actual configuration. Mean annual solar power production is approximately 6% higher in the maximum generation scenario as compared to the initial Vermont configuration while wind power generation nearly doubles. The random placement scenario also yields slight improvements in both wind and solar PV mean annual generation as compared to the initial Vermont configuration, though the difference between the means (0.011) is smaller than the standard deviation of the random placement mean annual electricity generation (0.016).

	Max. generation	Random placement	Initial config.
Wind	0.727* ± 0.002	0.373* ± 0.016	0.366
FAPV	0.248 ± 0	0.238 ± 0	0.235
TPV	0.042 ± 0	0.040 ± 0	0.039
TOTAL	1.017 ± 0.002	0.651 ± 0.016	0.640

Table 2: Mean annual electricity generation (TWh) from hypothetical alternative Vermont wind and solar PV infrastructure arrangements. NOTE: For modeling simplicity, 150 MW_{AC} of wind turbine capacity (fifty 3 MW_{AC} wind turbines) were sited in the maximum generation and random placement scenarios. This puts the 'maximum generation' scenario and 'random placement' scenario at a 1 MW_{AC} advantage against Vermont's initial wind turbine nameplate capacity.

4.2 Land use impacts of Vermont SEG-compatible deployments

The rest of section 4 presents modeled expansions of Vermont wind and solar PV infrastructure using three siting methods. The first two siting methods used are the maximum generation and random placement methods described above; the third siting method used is named 'clustering'. The clustering siting method weights each grid box according to how much land is already occupied by a given wind or solar PV infrastructure type both within the grid box and and in neighboring grid boxes. Only infrastructure-type land use in adjacent, cardinal direction grid boxes is included in the weighting calculation and adjacent infrastructure-type land use is weighted at 50% as compared to the grid box's own infrastructure-type land use. The clustering siting method represents an approximate 'business as usual' wind and solar PV growth approach in which regions that currently host wind and/or solar PV infrastructure will receive more of it and areas that currently do not host wind and/or solar PV infrastructure will rarely, if ever, receive more. Siting of new wind and solar PV infrastructure under the clustering siting method, as with the other two siting methods, adheres to land use protections and competition for land availability among infrastructure types.

A total of twelve scenarios were generated using the REGS model, one for every combination of one of three siting methods and one of four Vermont SEGs as outlined at the start of section 4. Figures 7 and 8 show the deployment patterns of new wind and solar PV infrastructure for eight of the twelve scenarios. For brevity, the random placement scenarios are not depicted. Infrastructure siting patterns persist between the hypothetical maximum generation wind and solar PV configurations from the previous section and the expanded SEG-compatible deployments shown here. New wind turbines are located almost exclusively along the spine of the Green Mountains (figures 7A through D) to harness the Vermont's peak mean wind speeds and solar PV panels are predominantly located in Windsor and Windham counties (figures 8A through D) in line with Vermont's peak mean irradiance values. As annual electricity generation targets rise, wind turbines steadily saturate the best wind energy resource locations along the Green Mountains and begin to spread to Essex County in northeastern Vermont (figure 8D). Clustering-driven siting for wind (figures 7E through H) and solar PV (figures 8E through H) largely follow the spatial pattern set by Vermont's initial wind and solar PV infrastructure configuration. Wind turbine siting in these scenarios results in large, localized deployments surrounding the four existing clusters of wind turbines that grow steadily as electricity generation targets rise. New solar PV panel installations are much more diffuse throughout Vermont thanks to the state's initial solar PV panel distribution. A few individual grid boxes in Chittenden and Rutland counties exceed MW_{AC} of solar PV panel nameplate capacity and 0.5 km^2 of total solar PV land use (figure 8H).

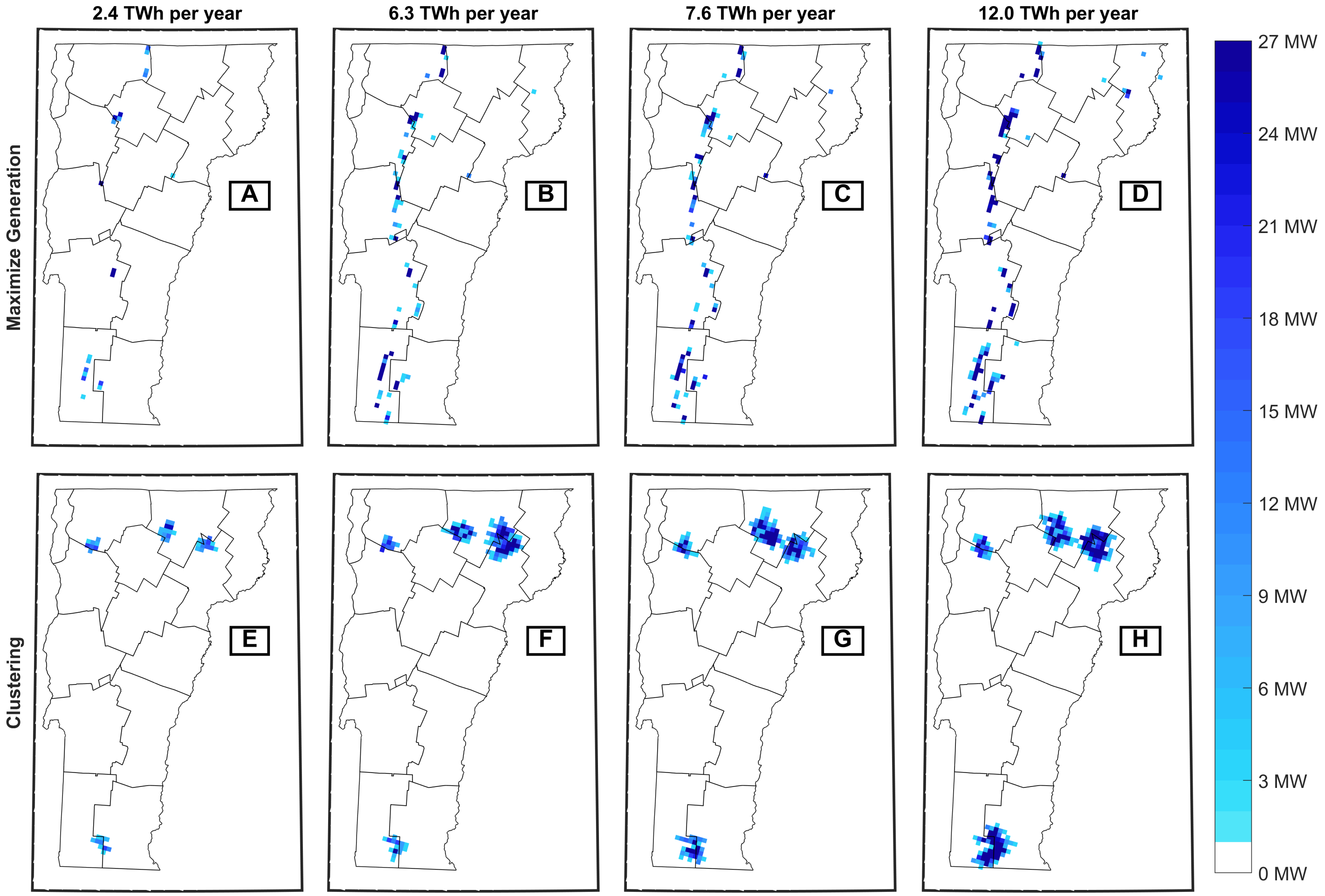

Figure 7: Total modeled Vermont wind turbine infrastructure growth under maximum generation and clustering siting methods

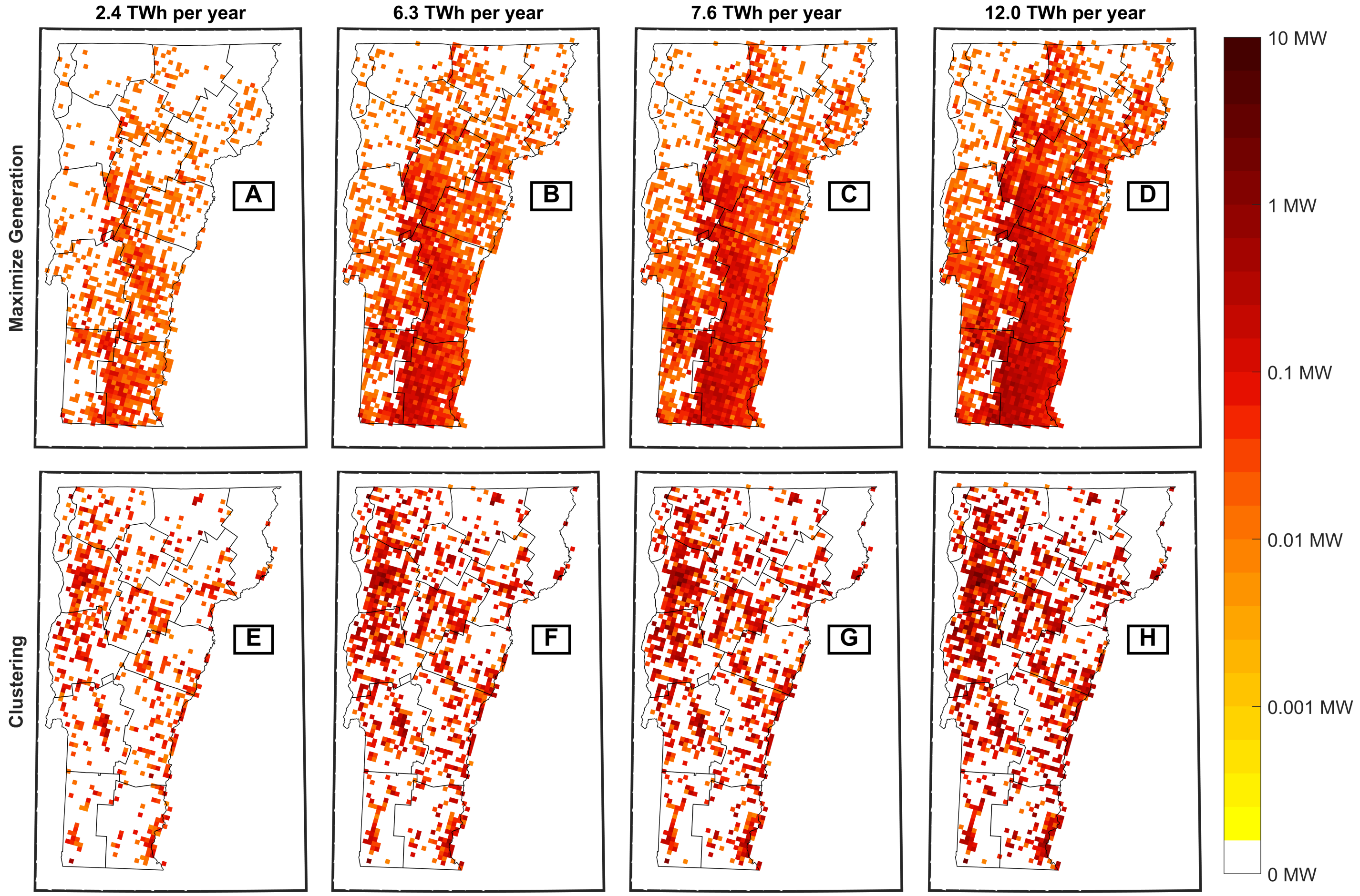

Figure 8: Total modeled Vermont solar PV panel infrastructure growth under maximum generation and clustering siting methods

Figures 9 reveals the mean wind and solar PV infrastructure requirements to meet each SEG. As expected, maximum generation siting achieved the SEG using the least amount of infrastructure across all four SEGs. As little as 0.92 GW_{AC} of wind and solar PV infrastructure, including the 0.34 GW_{AC} of infrastructure already installed, is sufficient to meet the first SEG of meeting 100% of Vermont's annual electricity needs through renewable energy resources. In contrast, both the random placement and clustering siting methods require over 1.2 GW_{AC} of total wind and solar PV infrastructure. This approximately 35% jump in total infrastructure requirements between the maximum generation and the random placement/clustering siting method grows to over 44% for the three higher SEG thresholds. The disparity is such that a nearly equivalent amount of wind and solar PV infrastructure (approximately 4.3 GW_{AC}, or more than ten-fold the amount of existing wind and solar PV infrastructure in Vermont presently) could either be used to generate 7.6 TWh of electricity per year under a random siting regime or nearly 12.0 TWh of electricity per year when sited to maximize generation. Clustering siting scenarios only marginally outperform random placement scenarios across the four SEG thresholds, largely due to the placement of existing wind turbines in sub-peak wind resource regions.

Figure 10 shows the corresponding mean land area needed to accommodate each SEG-compatible infrastructure deployment. Land use requirements scale linearly with nameplate capacity because of the fixed land use per unit nameplate capacity and fixed FAPV to TPV to wind turbine capacity parameterizations. As little as 11 km^2 of direct land use is needed to accommodate a SEG-compatible 2.5 TWh/yr infrastructure configuration, which represents less than 0.1% of Vermont's total eligible land area. The most aggressive SEG target and largest land footprint infrastructure deployment combination, 12 TWh/yr achieved through random placement, requires only 77 km^2 [0.42%] of Vermont's eligible land. The equivalent maximum generation siting scenario only requires 53 km^2 [0.29%] of Vermont's eligible land.

Of the three infrastructure types modeled, wind turbines directly occupy far less land per unit of nameplate generation capacity as compared to FAPV and TPV panels. Across all twelve test scenarios, wind turbines represent 44.4% of the total nameplate generation capacity and at

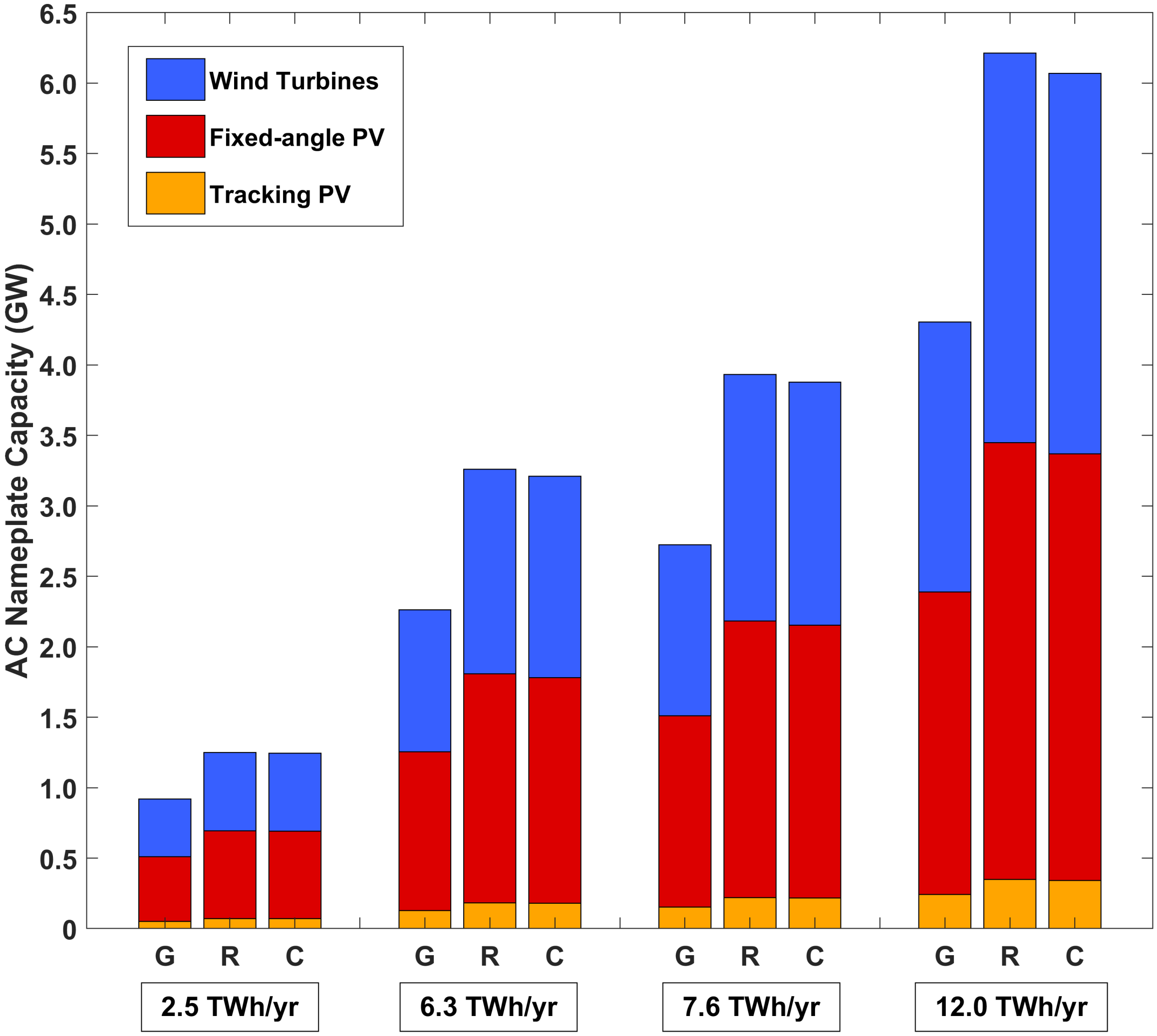

Figure 9: Nameplate capacities of SEG-compatible wind and solar PV infrastructure deployments. G: maximum generation siting; R: random placement; C: clustering.

least 57% of the mean annual electricity generation but only 4.3% of the total infrastructure land use footprint. In Vermont's case, this makes wind turbines a superior choice relative to solar PV panels of either type for maximizing annual electricity generation returns and minimizing land use. This does not mean, however, that wind energy is without its landscape impacts; this topic is revisited in depth in the proceeding discussion section. Furthermore, the relative strength of the wind and sunlight resources in a particular region will strongly influence the advantages of wind turbines to solar PV panels in electricity generation per unit land. Finally, the abundance or scarcity of a region's highest quality wind and sunlight resources will modulate how advantageous one

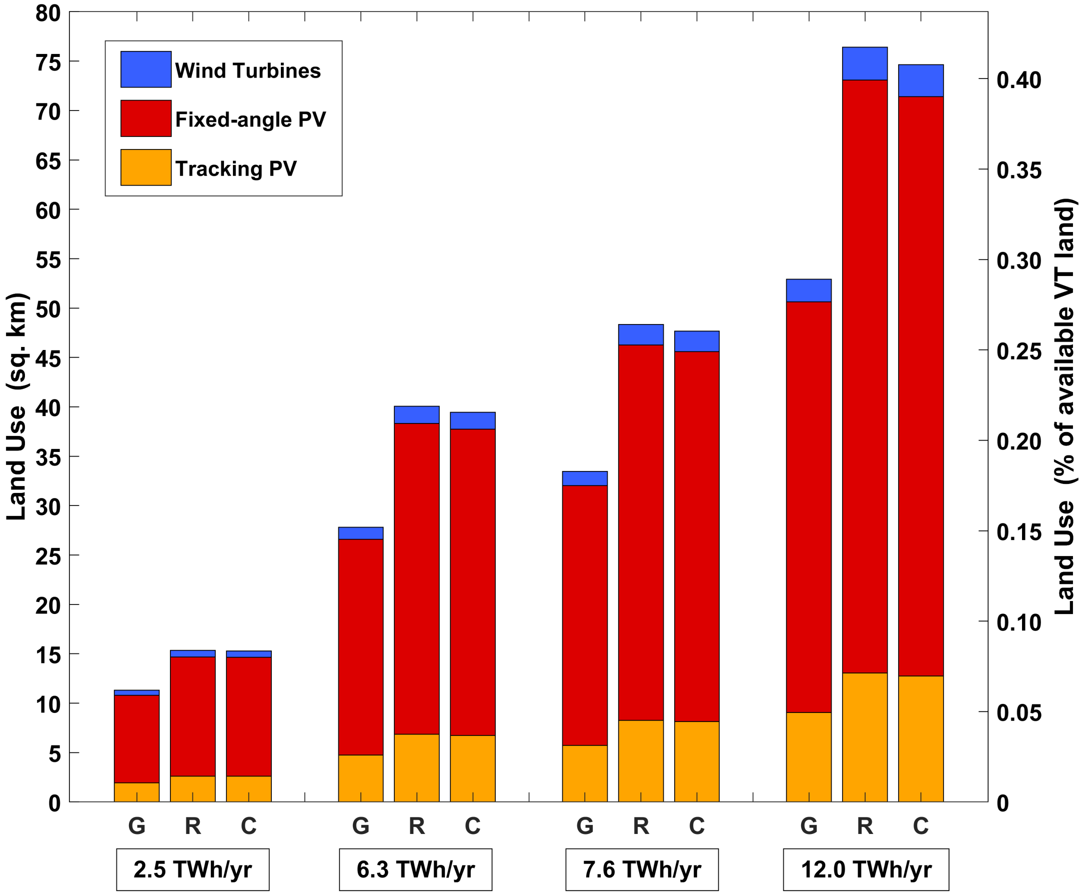

Figure 10: Land use requirements of SEG-compatible wind and solar PV infrastructure deployments. G: maximum generation siting; R: random placement; C: clustering.

infrastructure type is over another as total electricity generation targets increase. In the Vermont case, the state's highest quality wind and sunlight resources are not significantly exhausted in meeting the four SEGs tested due to the state's relatively low population density (reducing the amount of infrastructure and therefore land needed to meet SEGs) and the proportionally large areas of the state that have the highest mean wind speeds and sunlight exposure. Further comments on the specificity of this case study's findings to Vermont can be found in the proceeding discussion section.

4.3 100% wind and 100% solar PV deployments

We now examine two alternative infrastructure growth ratios under the same siting strategies to capture a more complete range of potential SEG-compatible wind and solar PV infrastructure deployment pathways. A wind-only or solar PV-only infrastructure deployment would be the only viable paths to achieving a SEG-compatible wind and solar PV-powered electricity system under a strict statewide constraint on development of one or the other infrastructure type. Examples of these constraints could include severe disruption of wind turbine or solar PV panel manufacturing, a legislative moratorium on further wind turbine or solar PV panel installation, and a grid operator-imposed moratorium on intermittent electricity generator interconnections.

Figure 11 shows how wind-only and solar PV-only infrastructure additions would satisfy Vermont's 12.0 TWh/year SEG under the maximum generation, random placement, and clustering siting methods. The spatial patterns of new infrastructure siting in these scenarios are consistent with those found previous scenarios. In figures 11B, 11D, and 11E, almost all of Vermont receives some new infrastructure except for grid boxes that fall entirely within protected parcels of land. Wind turbine clustering, as seen in figure 11C, shows that areas in Caledonia, Orleans, Windham, and Franklin counties that are as much as 24 kilometers away from existing wind turbine installations at present now have substantial wind turbine infrastructure installations. Though the total amount of land occupied by these high penetration scenarios on a statewide and gridbox by gridbox basis is relatively low, it is clear that large-scale wind turbine and solar PV panel deployments will impact Vermonters and Vermont landscapes in every county and almost every community in the state.

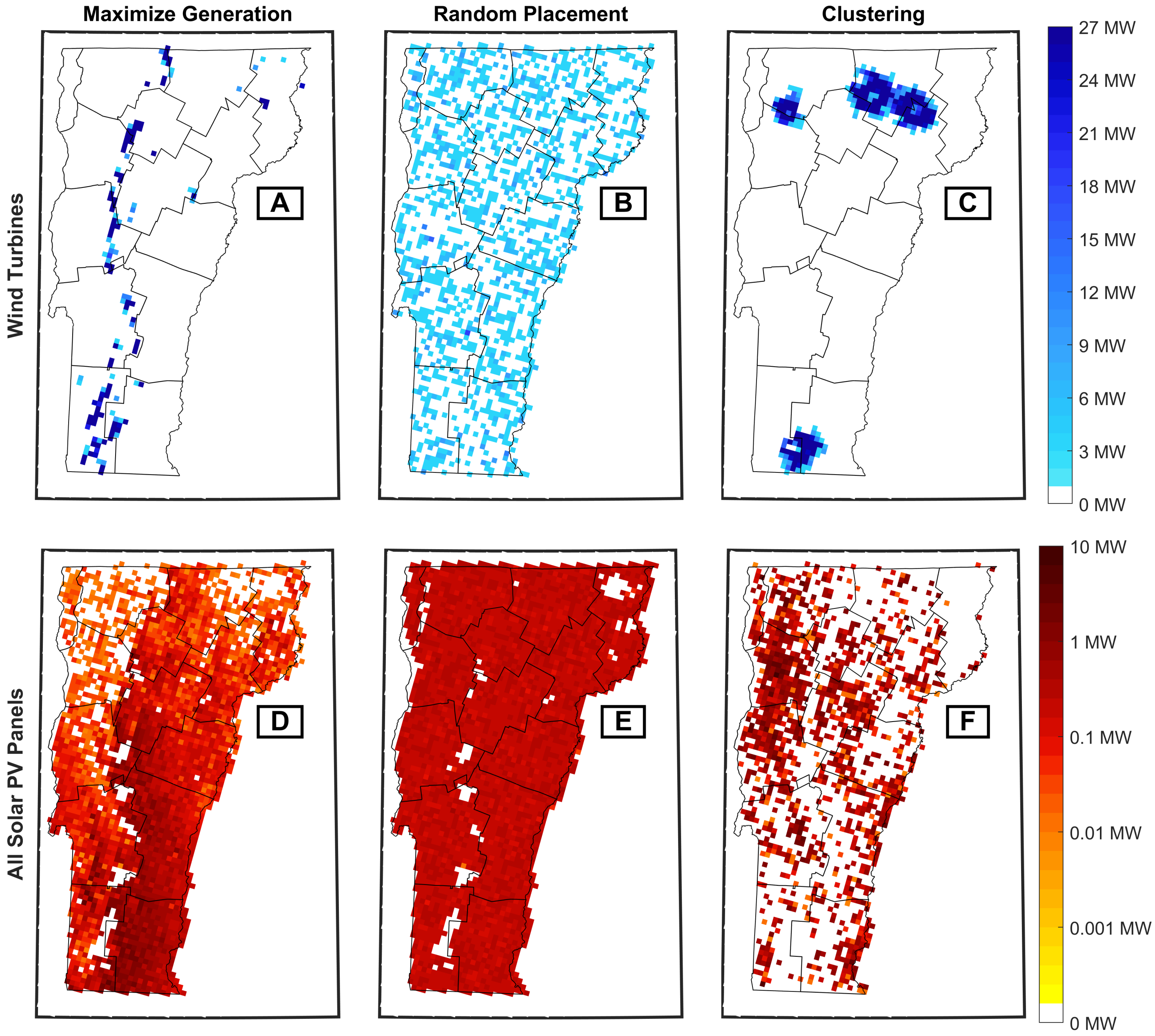

Figure 11: 100% wind turbine and 100% solar PV panel deployments to meet Vermont’s 12.0 TWh/yr SEG

Total nameplate capacity requirements for meeting 12.0 TWh/year of electricity generation rise sharply when implementing an all solar PV panel deployment as compared to a mixed infrastructure scenario (see figure 12). Whereas just 4.3 GW_{AC} of wind and solar PV infrastructure is needed under the current ratio, maximum generation scenario, over 7.4 GW_{AC} of new solar PV panels are required under the solar PV-only, maximum generation scenario. In contrast, the wind-only, maximum generation scenario requires less than 3 GW_{AC} of new wind turbines to be constructed.

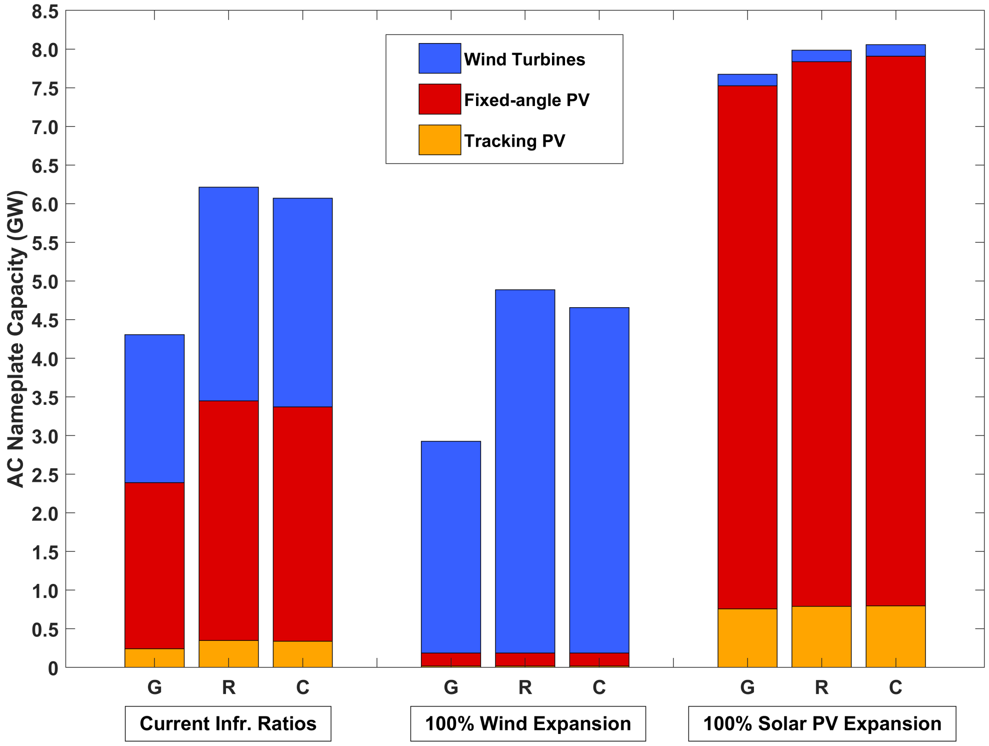

Figure 12: Nameplate capacities of 12.0 TWh/yr SEG deployments. G: maximum generation siting; R: random placement; C: clustering.

Land use requirements of the wind-only and solar PV-only infrastructure deployments are shown in figure 13. While many of the scenarios tested here produced infrastructure deployments that spread over most or all of Vermont, none of the test scenarios resulted in total wind and solar PV land use exceeding 1% (183 km^2) of Vermont's eligible land. Among scenarios that site at least some wind turbines, no scenario exceeded 0.5% of (92 km^2) Vermont's eligible land. Once again, wind turbines offer the highest nameplate capacity to direct land use efficiency in Vermont. For example, the wind-only, maximum generation scenario occupies just 7.3 km^2 of land, less than double the land occupied by all of Vermont's existing wind and solar PV infrastructure.

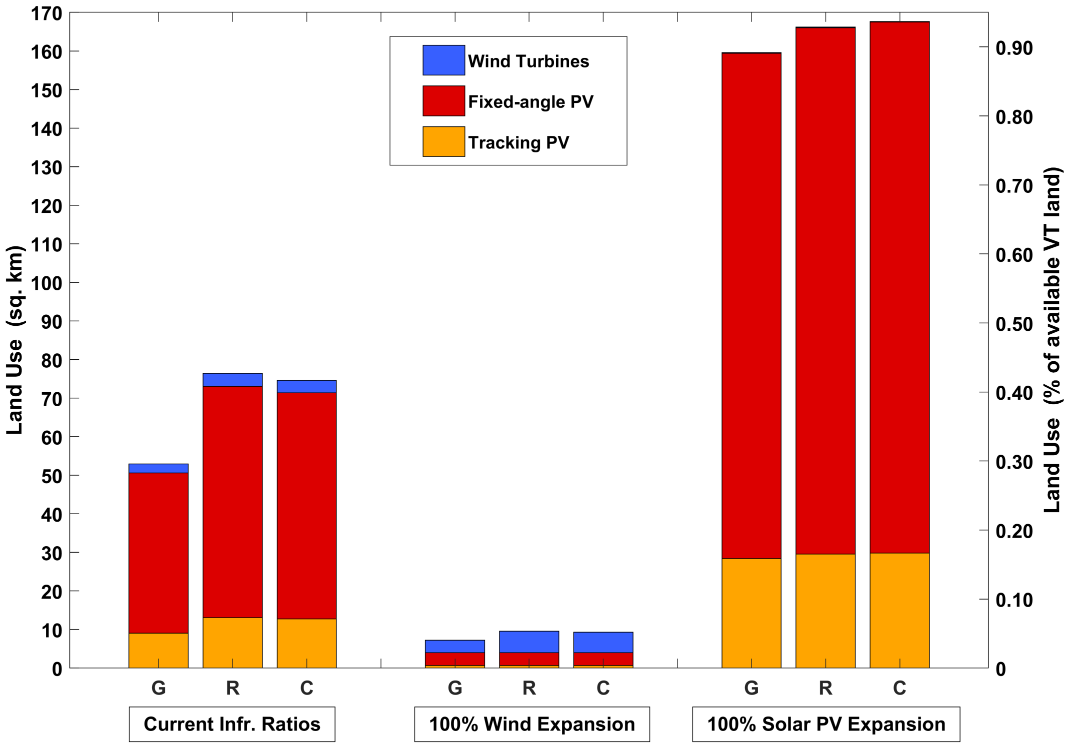

Figure 13: Land use requirements for 12.0 TWh/yr SEG deployments. G: maximum generation siting; R: random placement; C: clustering.

4.4 Assessing wind and solar PV deployments versus hourly load

Finally, we examine each wind and solar PV infrastructure deployment scenario for its performance relative to real hourly Vermont load data. Modeled hourly electricity generation data for the years 2013 to 2017 are compared to real Vermont statewide hourly load data for the same period to assess the effectiveness of all 21 test scenarios in satisfying hourly load in the absence of energy storage and other electricity generation resources. Figure 14 shows that across all test scenarios except for the 2.4 TWh/year and 100% solar PV deployments, maximum generation siting method deployments yield increased annual load satisfaction of between 5 and 8% relative to random siting and clustering siting method deployments. In the remaining two scenario groups, each siting method yields nearly identical load satisfaction performance (approximately 43% and 52% of total load met, respectively) but for different reasons. In the 2.4 TWh/year scenarios, there are very few hours in which load is completely met by wind and solar PV, meaning that almost all of the 2.4 TWh of electricity generated per year by each configuration is used to meet load. As figure 15 confirms, only a negligible amount (less than 0.005 TWh [0.9%]) of annual electricity generation is produced in excess of hourly load over the entire five year test period. Conversely, the 100% solar PV scenarios generate enormous amounts of surplus electricity generation (in excess of 9 TWh [75%]) per year. The over 7 $\mathrm{GW_{AC}}$ of solar PV panels placed across Vermont in these scenarios (see figure 12) easily meet and exceed Vermont's hourly load during most daylight hours but are incapable of generating electricity at night, thus leaving unavoidable deficits in load satisfaction. Also of note is the inferior performance of the wind-only and solar PV-only scenarios relative to the 12.0 TWh/year, current ratio scenarios. This result suggests that there are some advantages in leveraging a mix of wind and solar PV infrastructure for satisfying load as compared to wind-only and solar PV-only infrastructure deployments.

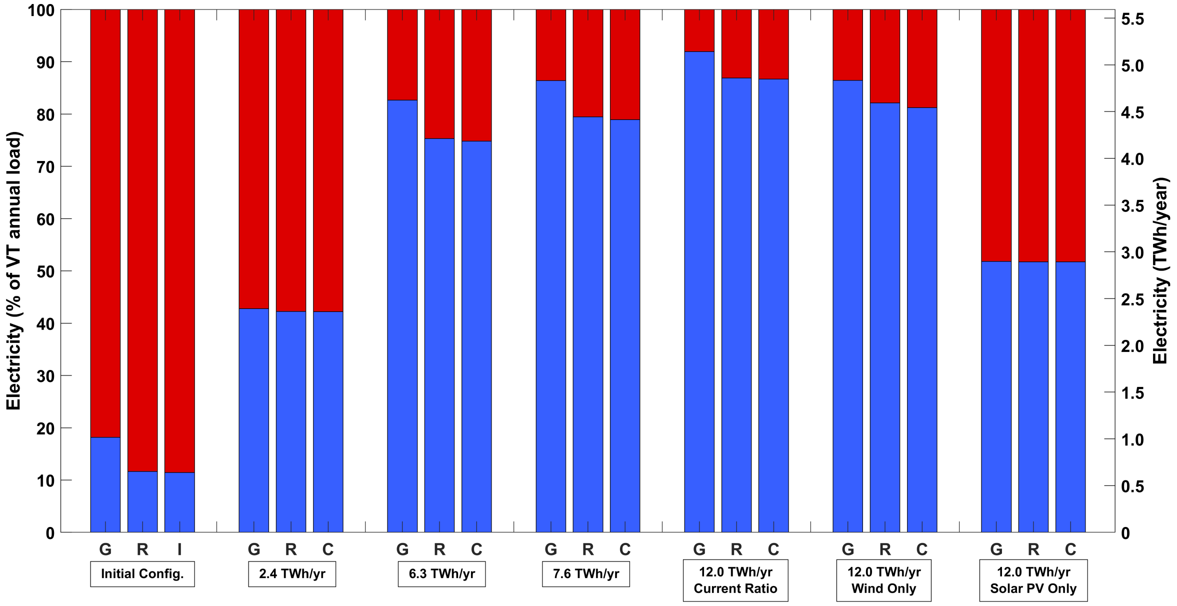

Figure 14: Mean annual Vermont load met by in-state wind and solar PV. G: maximum generation siting; R: random placement; I: Initial Configuration; C: clustering.

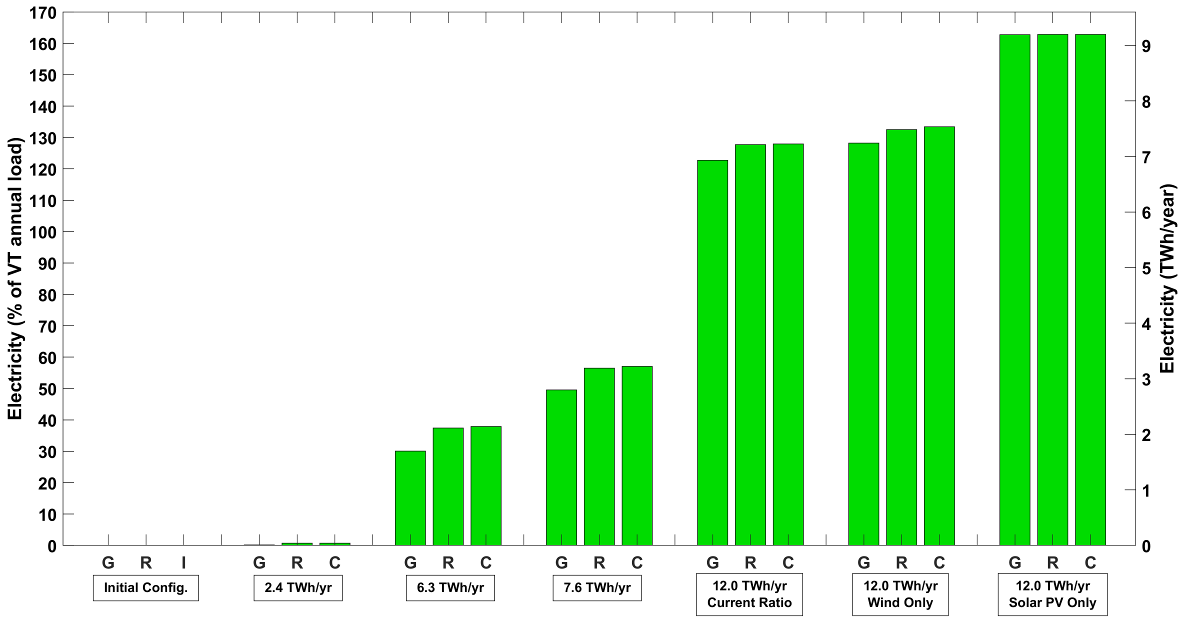

Figure 15: Mean annual surplus electricity generation for Vermont wind and solar PV versus hourly load. G: maximum generation siting; R: random placement; I: Initial Configuration; C: clustering.

Figures 14 and 15 also reveal that as increasing amounts of wind and solar PV infrastructure are installed, regardless of siting strategy, the marginal increases in load met by wind and solar PV decrease sharply. The approximately 2 GW_{AC} of additional wind and solar PV nameplate capacity in the 6.3 TWh/year, maximum generation scenario relative to the initial wind and solar PV infrastructure configuration carries annual load met from 18.1% to 82.5%. The next 2 GW_{AC} of additional wind and solar PV nameplate capacity needed to achieve the 12.0 TWh/year threshold yields only a 9.3% increase in annual load met to 91.8%. The principle cause of this pattern is the frequency of low wind, low (or no) sunlight weather conditions. Given an infinite amount of wind and solar PV infrastructure, there are some hours in which winds are calm, the sun does not shine, and wind and solar PV generators cannot produce electricity. These events, though infrequent, are inescapable hindrances for even large-scale wind and solar PV infrastructure deployments, particularly in relatively small geographic domains [38].

Figure 16 shows how each test scenario performs on a per-unit nameplate capacity basis with respect to overall electricity generation and load met. While electricity generation figures remain steady as each SEG is satisfied, marginal load satisfaction per unit of wind and solar PV infrastructure decreases steadily. Load satisfaction efficiency drops from 1,900 kWh per kW_{AC} in the real-world initial configuration to just 1,200 kWh per kW_{AC} in the 12.0 TWh/year, maximum generation scenario. Even the 100% wind energy scenarios, where electricity generation per unit capacity is well over 4,000 kWh per kW_{AC}, suffer degraded per-unit load satisfaction efficiency relative to the initial configuration. This trend comports with the diminishing marginal returns on new wind and solar PV infrastructure discussed above.

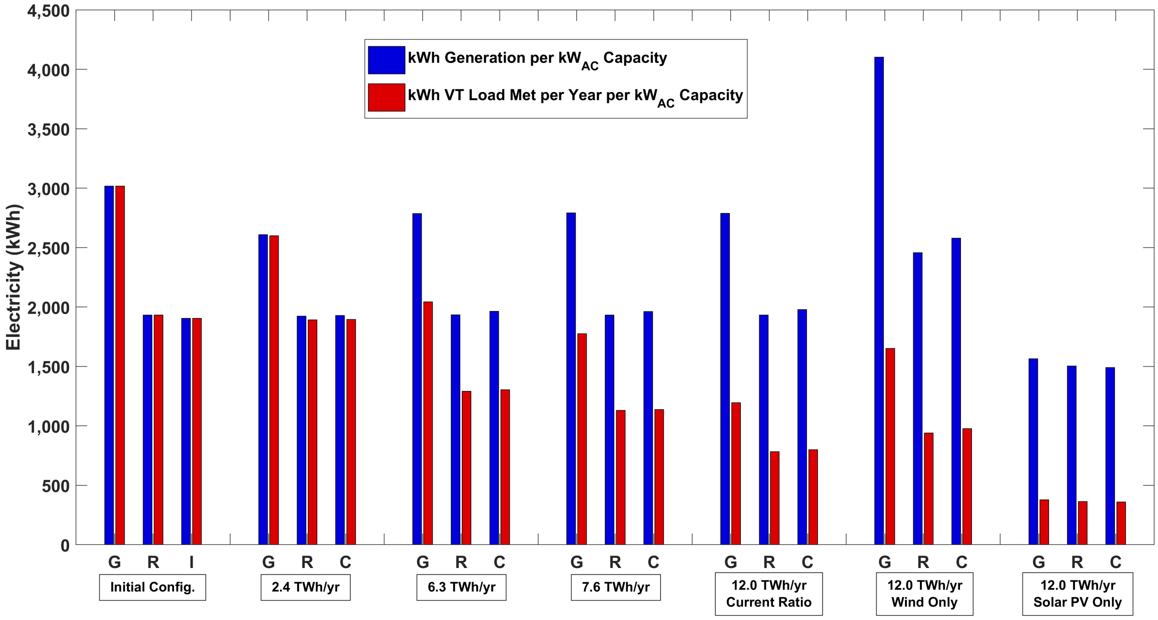

Figure 16: Vermont wind and solar PV electricity generation and load satisfied per kW_{AC} nameplate capacity.

5 Discussion

The foregoing case study demonstrates how more granular modeling of wind and solar PV infrastructure, the land use this infrastructure incurs, and the weather conditions this infrastructure relies upon for electricity generation can enable more realistic and tangible formulations of SEG-compatible electricity systems. The methods described here can be utilized anywhere in CONUS, provided that sufficient information about the location, size, and type of existing wind and solar PV infrastructure can be collected. Analyses of other states and regions in North America to compare and contrast with Vermont were hampered by the lack of datasets equivalent to [32]. The diversity of potential pathways for meeting SEGs and broader goals like the "rapid and far-reaching transitions" called for by the IPCC means that this work only represents one part of the process for finding and delivering a consensus electricity system decarbonization solution [1]. Moreover, the solution that works for one region or community may not work for another. Based on the outcomes of this case study, wind turbines appear to be a superior choice for meeting Vermont's electricity needs in terms of operational efficiency (i.e. meeting electricity demand when it is demanded) and land use efficiency. This outcome should not be construed as a recommendation for Vermont to deploy wind turbines hastily or exclusively, nor is it a blueprint for the whole of North America to follow. Each region has different population levels, energy demand patterns, wind and sunlight resources, electric grid capacities, preferences, priorities, and so on; there is no one-size-fits-all solution. Instead, the Vermont case study demonstrates in general terms how the distance between energy policy goals and initial conditions can be bridged. The ultimate utility of this information is then unlocked when its findings are used to inform and initiate further analyses and stakeholder discussions. It is from these processes that the ultimate electricity system decarbonization pathways will be determined. To that end, we will now discuss a range of additional topics that interlock with and overlap the work undertaken here.

As noted, the Vermont case study shows that, among the three infrastructure types modeled, wind turbines provided both large, consistent electricity generation returns and minimal direct land use impacts. This will also be true of other regions of North America that have strong wind resources and particularly true of other locations with similar or lower quality sunlight resources. The full landscape impacts of wind energy are not fully captured in the above case study, however. As discussed briefly in section 2.3, wind turbine towers only directly occupy small parcels of land. Secondary land uses, both temporary and permanent, due to site preparation, service roads, and support infrastructure can significantly expand the true footprint of wind turbine installations. The visual impacts of wind turbine towers and rotating blades are also not captured in the model. These impacts represent a significant source of resistance to wind turbine siting among communities in Vermont and elsewhere. While the REGS model uses a rudimentary measure of wind turbine crowding to prevent oversaturation, it does not capture the potential visual impacts of wind turbines which undoubtedly influence the viability of some locations for receiving wind turbines [39] [40]. This is particularly true for many of the highest electricity generation locations in Vermont which are also typically the highest elevation locations in Vermont and therefore among the most visible locations in Vermont. Making like for like comparisons between wind turbines and solar PV panels in terms of land use is thus a somewhat flawed exercise. Better capturing the total landscape-level impacts of wind energy in future modeling iterations is a worthy area for future work.

Another key aspect of new energy infrastructure deployments to consider is the lifespan of the infrastructure. Like any other infrastructure type, wind turbines and solar PV panels have limited effective lifespans and must be replaced periodically. Wind turbines and solar PV panels typically have lifespans of between 20 and 30 years [41]. Once a wind turbine or solar PV panel array is due to be replaced, its electricity generation capacity is lost until new infrastructure is installed or a new installation is made elsewhere. This process is not captured in the REGS model since the model develops individual snapshots of infrastructure deployments rather than timeseries. While infrastructure replacement means that more efficient wind turbines or solar PV panels can be installed, it also allows for land leases to expire and generation capacity to be lost. Capturing these factors in future modeling activities could also enhance the utility of this work.

Rooftop solar PV panels are not distinguished from ground-mounted solar PV panels in this case study which means that rooftop solar PV panels incur land use. Quantifying rooftop solar PV panel siting suitability and electricity generation potential is an active area of research [42] [43]. More explicit modeling of rooftop PV panel siting could both improve the accuracy of the model and reduce the modeled land use footprint of solar PV panel infrastructure. This could enhance the relative strength of solar PV panels against wind turbines in land use efficiency evaluations and provide better estimates of a given region's potential rooftop solar PV capacity. Rooftop solar PV panels can also partially or completely meet local household electricity demand in some situations and, in aggregate, significantly influence the grid's net electricity demand levels. As rooftop solar PV panels and other 'behind the meter' energy resources become more prevalent, more elaborate modeling techniques for electricity demand would be worthy additions to analyses like this one.

Energy storage technologies, particularly batteries and electric vehicles, are also likely to significantly influence the growth and behavior of electricity systems. These technologies, along with generally growing electricity demand through electrification of non-electric energy consumption behaviors, will likely mean that some of the surplus electricity generated by the larger wind and solar PV infrastructure deployments tested above (15) could be harnessed rather than wasted through curtailment. At present, if too much electricity is fed into the grid by wind and solar PV generators, they may be instructed to curtail their generation so as not endanger other grid infrastructure through overloading. This is counterproductive for a number of reasons. For example, curtailed wind and solar PV electricity reduces the economic competitiveness of these energy resources and reduces the use of low-carbon and carbonless electricity generators. Energy storage technologies can absorb excess electricity at times of peak generation and help redistribute energy back into the grid during times of peak load. These devices would improve the efficacy of wind turbines and solar PV panels in meeting load and could reduce the amount of total nameplate generation capacity needed to fulfill electricity demands. This would, in turn, reduce the landscape impacts of electricity systems as a whole.

We have elected not to incorporate energy storage in this work as we feel it would significantly extend the scope of the work, add substantial modeling complexity, and stray from the paper's core purpose of assessing SEGs[4]. Instead, we feel this paper best serves as an enabler of further modeling and analysis in more focused areas, particularly power systems analysis, by grid operators, regulators, or other relevant stakeholders. Modeling of energy storage in this paper would entail making additional assumptions about future electricity load patterns, electric vehicle adoption, and interstate electricity trade. In addition, were large quantities of energy source capacity added to the grid, it is possible that their introduction would introduce a range of grid operation impacts across both the bulk transmission grid and local distribution lines. These topics represent significant additional work and their inclusion in this paper would further complicate the presentation of the scenarios tested which are already multifaceted with respect to infrastructure type, distribution, land use impacts, and performance relative to load.

We have also elected not to undertake explicit mathematical optimization analyses in this paper for similar reasons. As with the energy storage case, introducing optimization methods to the suite of test scenarios represents a significant extension of this paper's scope. Identifying optimal placements of new wind and solar PV infrastructure to meet SEGs with respect to one or more geospatial parameters, the electric grid, economic criteria, or other constraints is a worthy task, but one which can easily stand on its own in a separate paper. We believe this paper's outcomes and methods can be used to facilitate and more richly inform these efforts, particularly those undertaken by RTOs and ISOs. Specifically, we also believe that optimization with respect to certain parameters (e.g. maximizing electricity generation) could lead to overfitted solutions that are unlikely to be feasible to implement. For example, if a strictly optimal solar PV panel deployment were identified, the resulting infrastructure placements would fully saturate the 3km by 3km grid boxes that have the global maximum mean annual solar PV electricity generation potential and leave all other grid boxes unaltered, even those with only marginally inferior sunlight resources.

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[4] Vermont's SEGs are technology agnostic and make no mention of energy storage technologies. Given the potential of energy storage devices in supporting the deployment and utilization of wind and solar PV generation resources, it is possible that energy storage capacity requirements may be included in future SEGs in Vermont and elsewhere.

6 Conclusion

Deployment of renewable, low-carbon energy resources like wind and solar PV is already well underway in many parts of the world due to concerns over climate change, environmental and human health, and energy security. Governments are ratifying increasingly stringent SEGs to accelerate this process. Decarbonizing the electric grid and other energy demands through electrification will require orders of magnitude more wind and solar PV infrastructure to be installed, Understanding how distributed, intermittent electricity generators will impact the landscape and the grid is essential for streamlining the wind and solar PV implementation process.

This paper translates SEGs ratified by governments into a portfolio of specific, SEG-compliant wind and solar PV configurations and uses the state of Vermont as a case study. Each of the four SEGs examined can be achieved by wind and solar PV infrastructure configurations that directly occupy less than 1% of the state's land area. Vermont electricity demand was most effectively met by infrastructure configurations that prioritize electricity generation over other siting criteria. Configurations that relied solely on solar PV tended to perform least effectively versus electricity demand patterns and occupy the most land, while wind-only configurations were only marginally less effective in meeting demand than mixed configurations reflecting the state's current wind and solar PV infrastructure ratios. Diminishing returns in electricity demand satisfaction were observed across all configurations as they grew in total nameplate capacity, highlighting the inherent limitations of intermittent electricity generation resources.

Opportunities to extend and improve the efficacy of the REGS model include utilizing additional geospatial infrastructure siting criteria such as land use type, viewshed impacts, access to existing transmission infrastructure, wildlife habitat and migration zone protection, and so on. These indirect land use impacts are particularly important to capture for wind energy since the direct land use footprint of wind turbines per $\mathrm{MW}_{\mathrm{AC}}$ of generation capacity is minuscule as compared to solar PV panels. Incorporating wind and solar PV infrastructure lifespan limits, energy storage technologies, and rooftop solar PV panel siting could also enhance the utility of modeling results and provide more information to electric grid stakeholders of all types.

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