OPEN ACCESS

The 4th World Sustainability Forum
1 - 30 November 2014

http://www.sciforum.net/conference/wsf-4

World Sustainability Forum 2014 – Conference Proceedings Paper

Resource Potential and Land Use Tradeoffs of Renewable Electricity Development in Vermont, USA

Matthew J. Burke [1],*

[1] University of Vermont, Department of Community Development and Applied Economics, Gund Institute for Ecological Economics, 617 Main Street Burlington, Vermont 05405 USA

* Author to whom correspondence should be addressed; E-Mail: mburke2@uvm.edu; Tel.: +1-802-656-2906; Fax: +1-802-656-2995

Received: 29 August 2014 / Accepted: 31 October 2014 / Published: 3 November 2014

Abstract: The State of Vermont, USA seeks to expand the generation and use of renewable electricity over the coming decades. I apply a social-ecological-technical systems framework to investigate the resource potential and land use tradeoffs of development of in-state commercial-scale solar photovoltaic and wind electricity generation facilities in Vermont. Based on existing policy goals, I calculate number of facilities required and use spatial modeling and simulation to assess solar photovoltaic and wind resource potential, suitable siting patterns and tradeoffs between resource productivity and biodiversity. This assessment finds that Vermont will require from 178 to 1,527 - 2.2 MW solar photovoltaic facilities and an additional 9 to 76 - 20 MW wind facilities by 2032. Vermont's solar photovoltaic resource potential is equivalent to 18.9 percent of the state's total land area, and wind resource potential is equivalent to 3.1 percent of the state's total land area. Vermont holds sufficient solar and wind resource potential to support the state's renewable electricity policy goals. Renewable electricity development in Vermont will require confronting a tradeoff between use of areas with either lower resource potential or moderate biodiversity value. The conceptualization of Vermont's emerging renewable energy system as a social-ecological-technical system can guide future research and decision making.

Keywords: biodiversity; Dinamica, land use change; renewable energy; social-ecological-technical system; sustainable development; Vermont

---

1. Introduction

The State of Vermont, USA seeks to expand the generation and use of renewable electricity over the coming decades. Specifically, through the 2011 Vermont Comprehensive Energy Plan and related statutory legislation [1-2], the state of Vermont has adopted a diverse set of renewable energy (RE) goals including:

- that the target amounts of total RE shall be 55 percent of each retail electricity provider's annual electric sales during the year beginning January 1, 2017, increasing by an additional four percent each third January 1 thereafter, until reaching 75 percent on and after January 1, 2032;
- that Vermont can meet its energy service needs in a manner that is adequate, reliable, secure and sustainable, and that is environmentally sound;
- that development of RE uses natural resources efficiently and prioritizes related planned energy industries in Vermont, in particular, while retaining and supporting existing RE infrastructure; and
- that locates RE plants of small and moderate size in a manner that is distributed across the state's electric grid.

If Vermont is to achieve these policy goals, the state must rapidly innovate and develop an energy system that steadily shifts from nonrenewable to renewable sources in the coming decades. Given historical patterns in the state, nation and beyond, the challenge of achieving this scale of energy transition cannot be overstated. While Vermont ranks among the lowest states in the USA in total energy consumption per capita, reflecting end use patterns and limited industry [3], Vermont also relies heavily on nonrenewable sources to meet its energy demand.

Vermont's transportation and residential sectors each account for approximately one-third of the state's total energy consumption. Fuel oil and gasoline account for nearly all energy sources consumed by Vermont's transportation sector, a pattern extending back for at least half a century. Vermont's residential sector has seen a decrease in the use of fuel oil and an increase in wood biomass since 2004, yet natural gas and petroleum sources together account for more than 55 percent of the sector's current total energy consumption and more than three-quarters of Vermont's home heating consumption. Nuclear power accounts for 75 percent of Vermont's annual net electricity generation, hydropower accounts for nearly 15 percent and all other renewables the remaining approximately 10 percent [3-10].

Vermont's continued dependence on nonrenewable sources, particularly for heating and transportation, contributes to human and environmental impacts both within the state and beyond. Yet in transitioning, Vermont will also need to anticipate and address impacts of large-scale RE use, and tradeoffs of alternative RE systems. Direct impacts of extensive utilization of RE technologies include the social and ecological outcomes from land use and land cover change (LUCC) due to the development of generating facilities. While Vermont's energy system is currently highly dependent on nonrenewable resources [4], electricity generation presumably offers greater potential for increased renewable resource use in the short term [11]. I therefore focus on the electricity sector here.

I build from the work on social-ecological systems (SES) [12-13] to consider Vermont's emerging RE systems as a social-ecological-technical system [14-15]. Given the current understanding of Vermont's RE SETS and the state's policy goals, several research questions motivate the present work on direct land use tradeoffs of renewable electricity generation in Vermont. I define tradeoffs to signify situations in which a choice must be made between desirable but incompatible features. To consider direct social and ecological tradeoffs of the development of renewable electricity in Vermont, I formulate questions relevant to land use changes.

Q1: *How many generating facilities are required in Vermont to meet the goals of existing state policy?* I calculate the number of electricity generating facilities required in Vermont (U1: Number of user) under alternative supply portfolios as defined by the importance of the resource (U8) and the technology used (U9), and further determine the land area required for the facility footprints.

Q2: *What and where is the potential for large-scale in-state renewable electricity generation in Vermont?* I calculate the areal extent of Vermont's resource potential for large-scale solar PV and wind power development, and thereby describe the size of the resource system (RS3) and its spatial distribution (RU7).

Q3: *How does the potential Vermont in-state renewable electricity generation compare to the amount projected and targeted by existing state policy?* I compare the size of the resource system to (RS3) to the amount required (U8: Importance of resource). I hypothesize that sufficient resource potential is available in Vermont for all supply portfolios [16].

Q4: *Where might these facilities be suitably developed in Vermont?* I develop suitability maps combining available solar PV and wind resource potential data (RS3: Size of resource system) as grouped by classes of resource productivity (RS5: Productivity of system) with data layers describing biodiversity values (O2: Ecological performance measures). I use the suitability maps as spatial probability functions to simulate plausible development patterns of facilities using a land use and land cover (LUCC) change simulation model. For each LUCC simulation, I set alternative parameters defined by number of facilities required (U1: Number of users) and footprint of each facility (RS4: Human-constructed facilities). I hypothesize that varying parameters across scenarios results in distinct spatial transitions given the same probability functions [17].

Q5: *At what scale of renewable electricity generation in Vermont might we expect to confront tradeoffs?* I compare the alternative approaches and resulting tradeoffs when achieving the required extent of land use change, either through use of areas offering lower resource classes (RS5: Productivity of the system) or higher biodiversity values (O2: Ecological performance measures). I hypothesize that tradeoffs become apparent between resource productivity and biodiversity with even small increases in LUCC due to development of facilities.

2. Results and Discussion

2.1. Results and Key Findings

I calculated the number of solar PV and wind generating facilities required in Vermont (U1: Number of user) under each of the six alternative scenarios as defined by the importance of the resource (U8) and the technology used (U9) for 2032, and thereby estimated the land area required for the total facility footprints (Table 1). I present the results for Q1 here in order of land area required.

For the Solar All-Electric scenario, I found that Vermont would require 1,527 - 2.2 MW solar PV facilities and 25 - 20 MW wind facilities by 2032. This scale of development would require an estimated land area of 9,658 hectares, including 9,217 hectares for solar PV facilities and 441 hectares for wind facilities.

For the Wind All-Electric scenario, Vermont would require 509 – 2.2 MW solar PV facilities and 76 – 20 MW wind facilities by 2032. This scale of development would require an estimated land area of 4,395 hectares, including 3,073 hectares for solar PV facilities and 1,322 hectares for wind facilities.

For the Solar Business-as-Usual scenario, Vermont would require 628 – 2.2 MW solar PV facilities and 10 - 20 MW wind facilities by 2032. This scale of development would require an estimated land area of 3,971 hectares, including 3,790 hectares for solar PV facilities and 181 hectares for wind facilities.

For the Solar Low-Electric scenario, Vermont would require 535 – 2.2 MW solar PV facilities and 9 - 20 MW wind facilities by 2032. This scale of development would require an estimated land area of 3,384 hectares, including 3,229 hectares for solar PV facilities and 154 hectares for wind facilities.

For the Wind Business-as-Usual scenario, Vermont would require 209 – 2.2 MW solar PV facilities and 31 – 20 MW wind facilities by 2032. This scale of development would require an estimated land area of 1,807 hectares, including 1,263 hectares for solar PV facilities and 544 hectares for wind facilities.

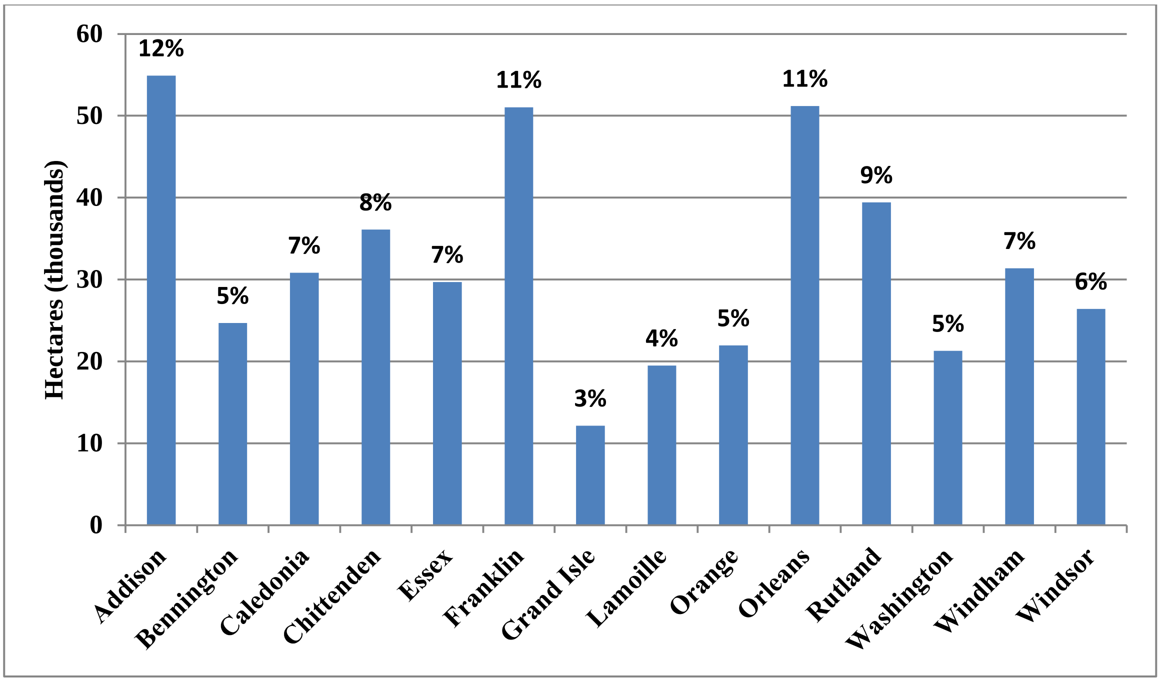
For the Wind Low-Electric scenario, Vermont would require 178 – 2.2 MW solar PV facilities and 26 – 20 MW wind facilities by 2032. This scale of development would require an estimated land area of 1,540 hectares, including 1,076 hectares for solar PV facilities and 463 hectares for wind facilities.

Table 1. Quantity and Land Area of Solar and Wind Facilities Required per Scenario

Scenario	Solar photovoltaic facilities (2.2 MW)		Wind facilities (20 MW)		Total area required in hectares (Percentage of total Vermont land area)
	Quantity	Area in hectares	Quantity	Area in hectares	
Solar-AE	1527	9217	25	441	9658 (0.40)
Wind-AE	509	3073	76	1322	4395 (0.18)
Solar-BAU	628	3790	10	181	3971 (0.17)
Solar-LE	535	3229	9	154	3384 (0.14)
Wind-BAU	209	1263	31	544	1807 (0.08)
Wind-LE	178	1076	26	463	1540 (0.06)

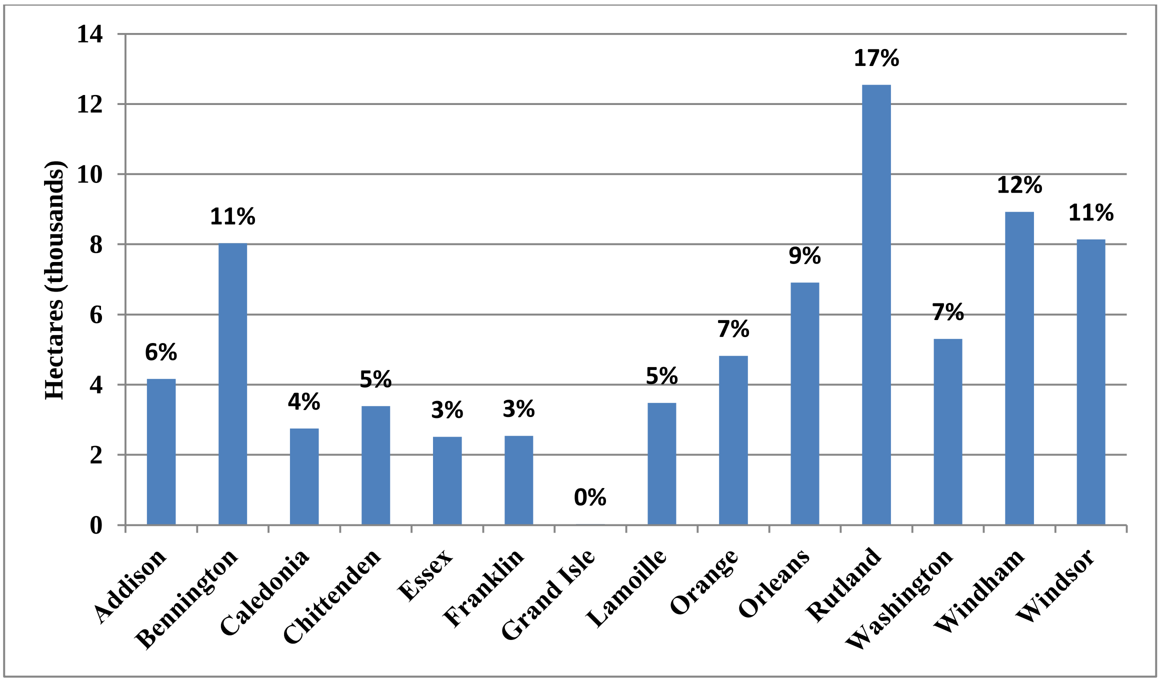
I calculated the areal extent of Vermont’s resource potential for large-scale solar PV and wind power development in order to describe the size of the resource system (RS3), as relevant to Q2. I estimated that Vermont’s solar PV resource potential includes approximately 0.45 million hectares, equivalent to 18.9 percent of the state’s total land area. The distribution of areal extant varies considerably from county to county, from 12.1 thousand hectares in Grand Isle County to 54.9 thousand hectares in Addison County (Figure 1).

Figure 1. Areal extent and percentage of total solar photovoltaic resource potential per Vermont county.



Vermont's wind resource potential includes approximately 73.5 thousand hectares, equivalent to 3.1 percent of the state's total land area. As with solar PV resource potential, the distribution of areal extant for wind resource potential varies considerably from county to county. At only 24.8 hectares total, Grand Isle County likely has negligible resource potential. However, four counties offer approximately 8 thousand hectares or more of wind resource potential, including Rutland County with more than 12.5 thousand hectares of potential land area (Figure 2).

Figure 2. Areal extent and percentage of total wind resource potential per Vermont county.

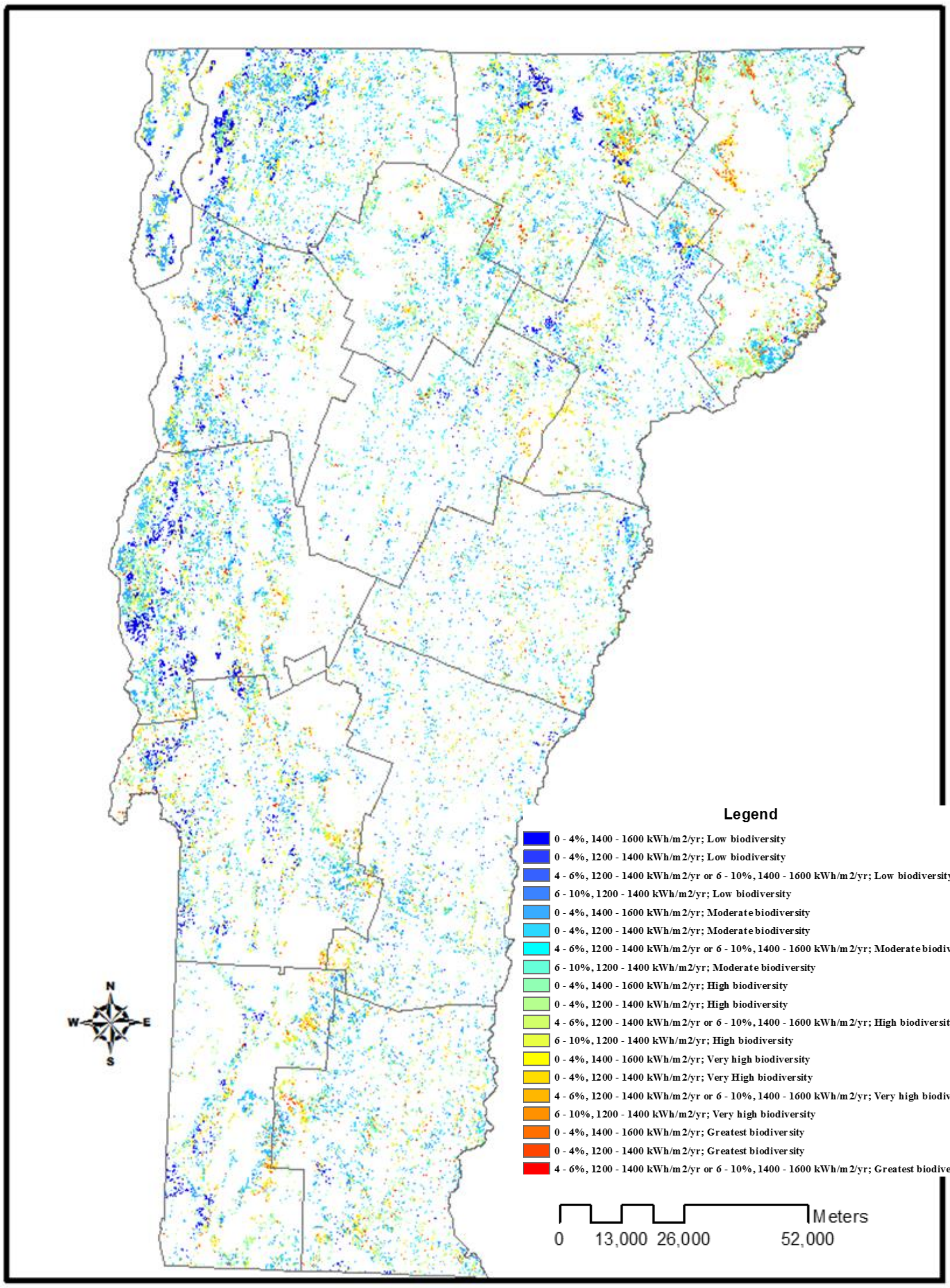


I compared the size of the resource system to (RS3) to the amount required (U8: Importance of resource) under varied supply portfolios, as defined by the state’s renewable energy goals (S4: Government resource policies) and alternative assumptions for the scope of the resource sector (RS1: Sector) and the technology used (U9). For the Solar All-Electric scenario, the required land area for development of facilities accounted for 2.05 percent of solar PV resource potential and 0.60 percent of wind resource potential in Vermont. For the Solar Business-as-Usual scenario, the required land area for development of facilities accounted for 0.84 percent of solar PV resource potential and 0.25 percent of wind resource potential in Vermont. And for the Solar Low-Electric scenario, the required land area for development of facilities accounted for 0.72 percent of solar PV resource potential and 0.21 percent of wind resource potential in Vermont.

For the Wind All-Electric scenario, the required land area for development of facilities accounted for 0.68 percent of solar PV resource potential and 1.80 percent of wind resource potential in Vermont. For the Wind Business-as-Usual scenario, the required land area for development of facilities accounted for 0.28 percent of solar PV resource potential and 0.74 percent of wind resource potential in Vermont. And for the Wind Low-Electric scenario, the required land area for development of facilities accounted for 0.24 percent of solar PV resource potential and 0.63 percent of wind resource potential in Vermont.

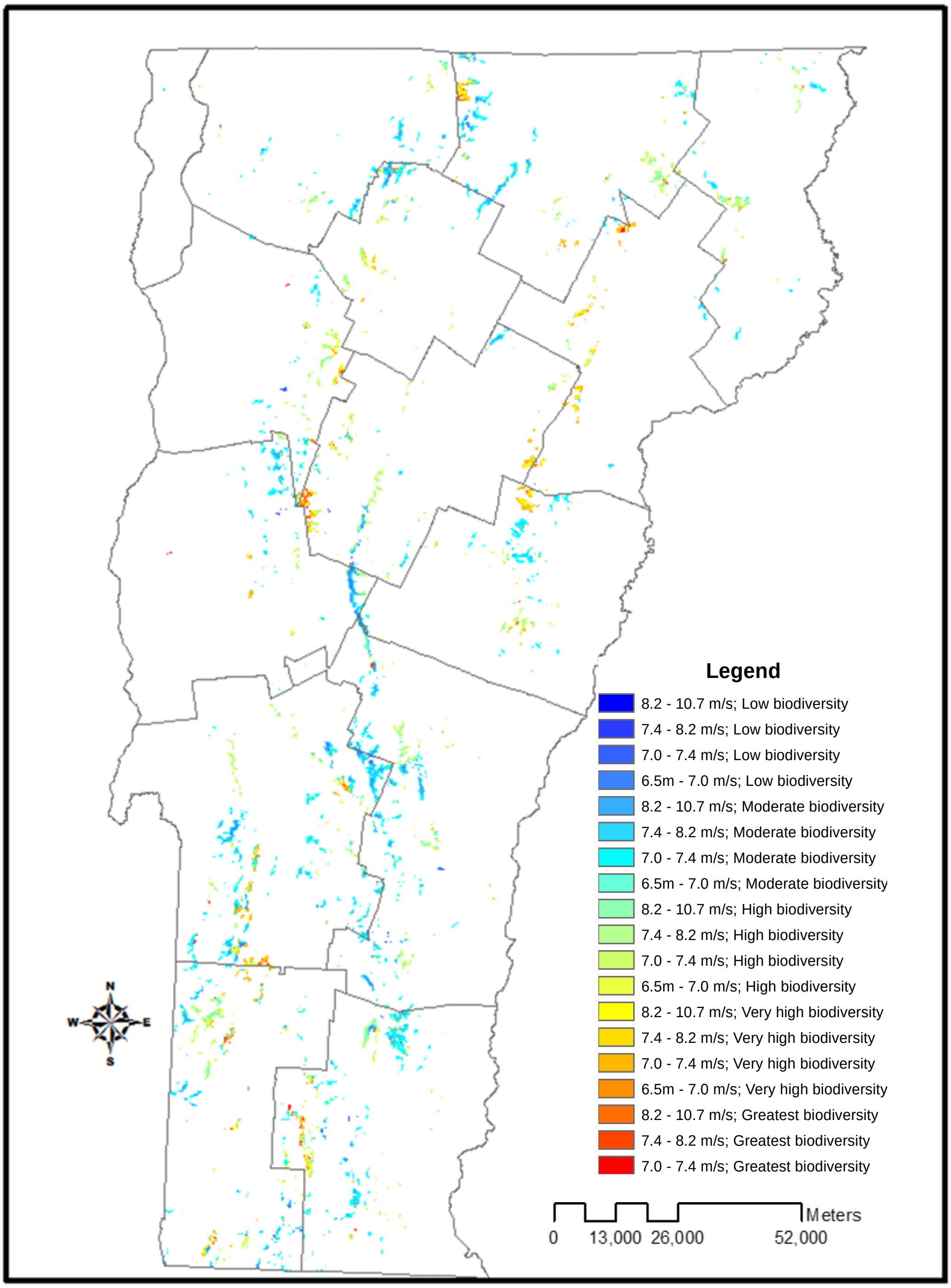
By combining each available solar PV and wind resource potential data (RS3: Size of resource system) as grouped by classes of resource productivity (RS5: Productivity of system) with data layers describing biodiversity values (O2: Ecological performance measures), I calculated the spatial distribution (RU7) of areas for suitable development of solar PV and wind facilities in Vermont. As defined by resource potential and biodiversity value (most suitable in blue; least suitable in red), the suitable areas for solar PV development were scattered widely across the state, with concentrations of suitable areas in the counties of the Champlain Valley in the northwestern half of the state and additionally in Orleans and Caledonia Counties in the northwestern region of the state (Figure 3).

Figure 3. Spatial distribution of suitable areas for solar photovoltaic development in Vermont.



Similarly defined, suitable areas for wind facility development were concentrated primarily within the central region of the state, following the ridgeline of the Green Mountains, with additional areas found in the northeastern and southwestern regions (Figure 4).

Figure 4. Spatial distribution of suitable areas for wind development in Vermont.



Each of the suitability maps were used as spatial probability functions to simulate spatial distribution (RU7) of facilities using a LUCC simulation model, with transition parameters defined by number of facilities required (U1: Number of users) and footprint of each facility (RS4: Human-constructed facilities). Each of the six scenarios produced a distinct spatial LUCC transition, supporting the hypothesis of Q4 that varying these parameters across scenarios will result in distinct spatial transitions given the same probability functions. The two All-Electric scenarios (Figures 5 & 8) appeared to produce distinctly different spatial patterns as compared to all other scenarios (Figures 6, 7, 9 & 10). Each LUCC transition pattern simulated a plausible development of solar PV and wind facilities for Vermont in 2032 based on the parameters defined here.

Figure 5. Simulated spatial distribution of solar photovoltaic and wind facilities for Solar All-Electric scenario.

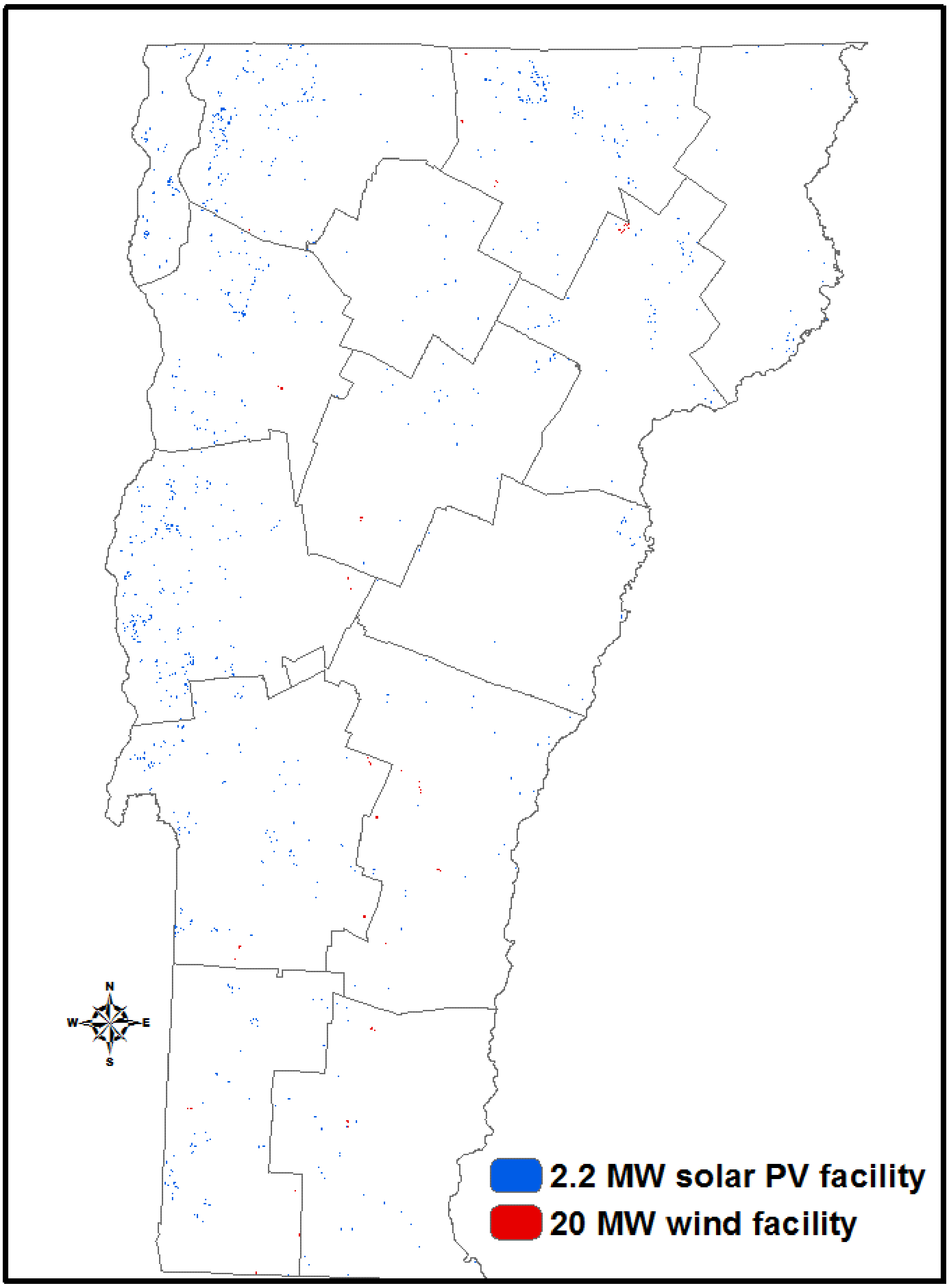


Figure 6. Simulated spatial distribution of solar photovoltaic and wind facilities for Solar Business-as-Usual scenario.

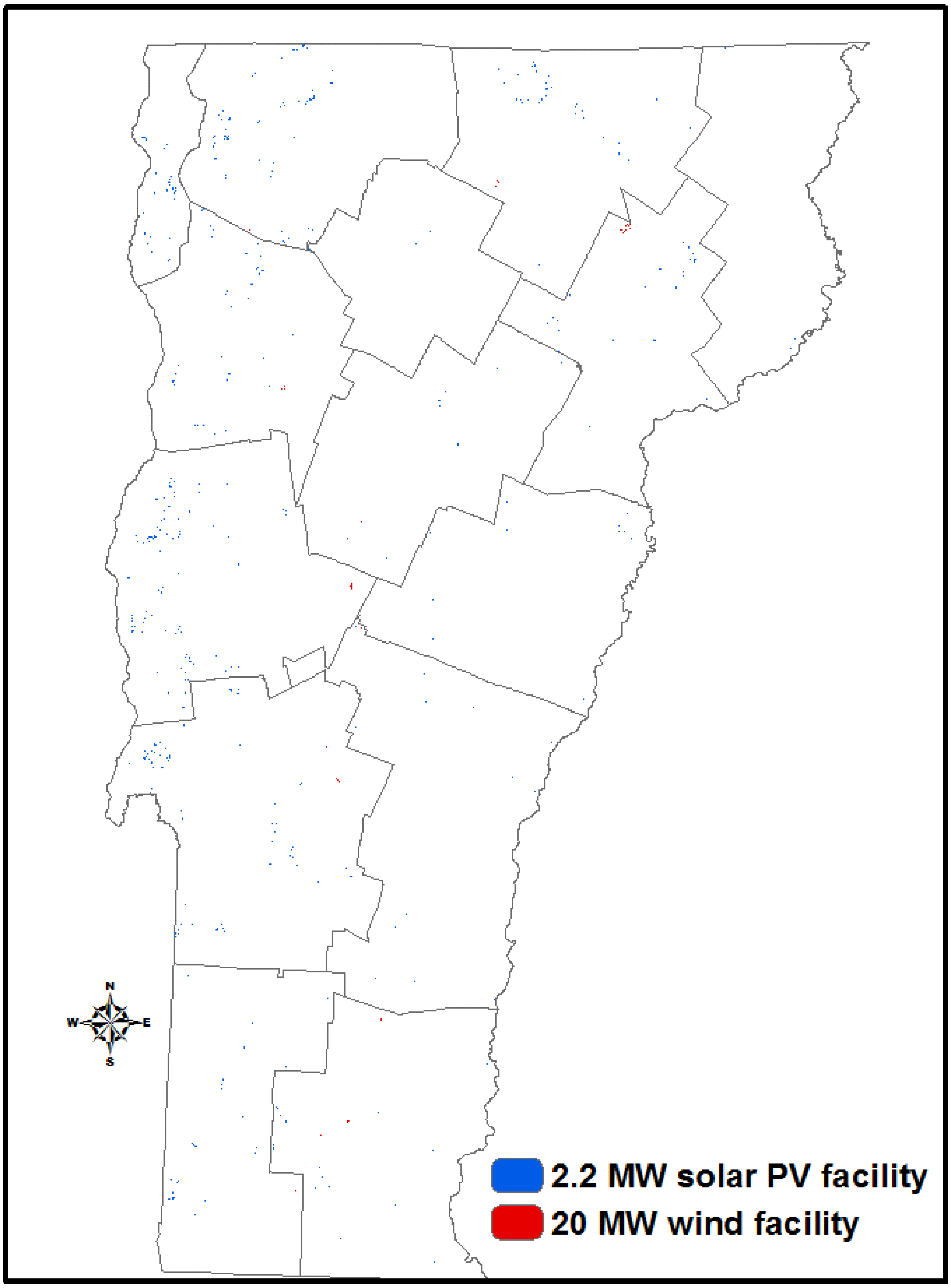


Figure 7. Simulated spatial distribution of solar photovoltaic and wind facilities for Solar Low-Electric scenario.

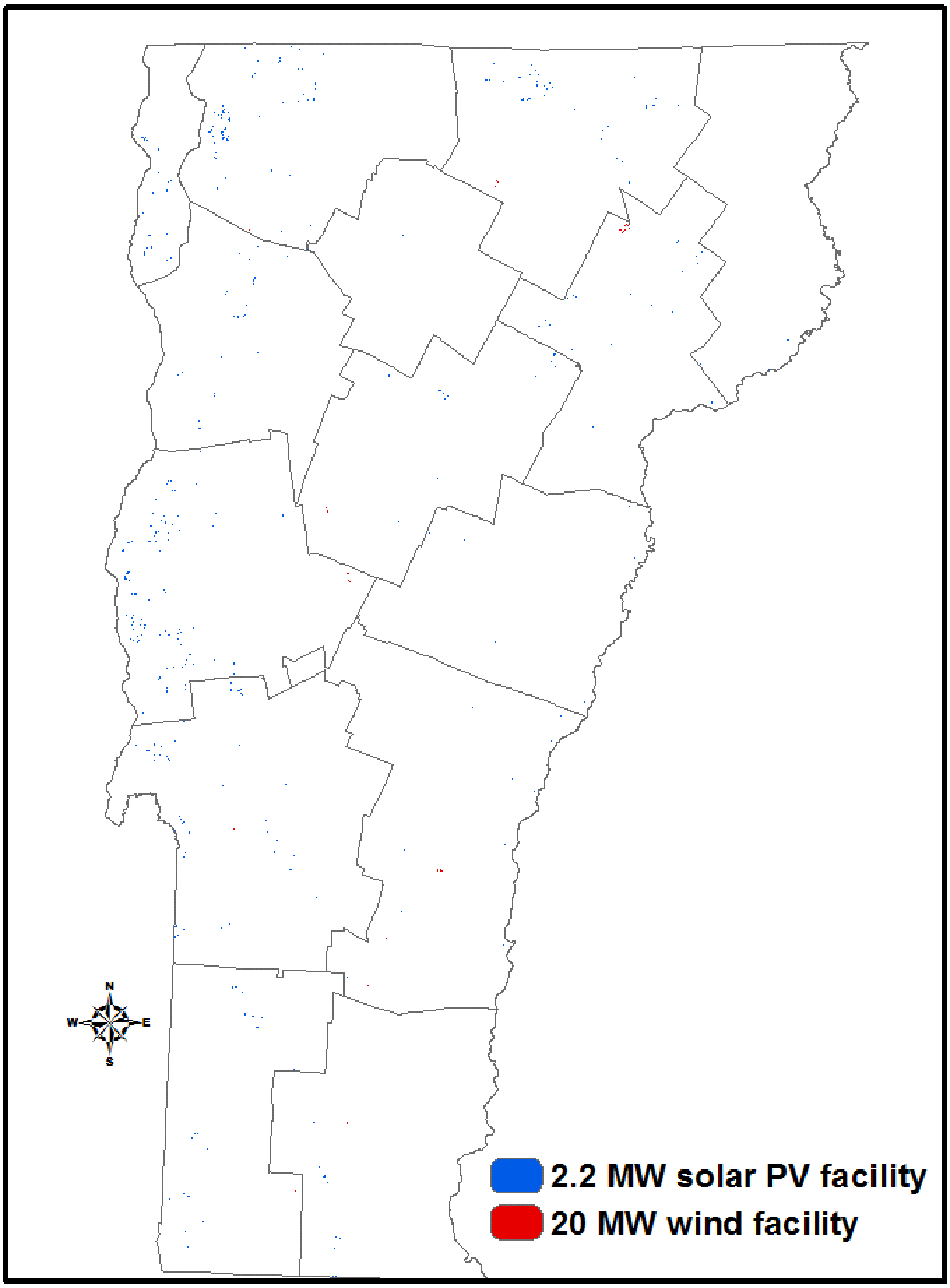


Figure 8. Simulated spatial distribution of solar photovoltaic and wind facilities for Wind All-Electric scenario.

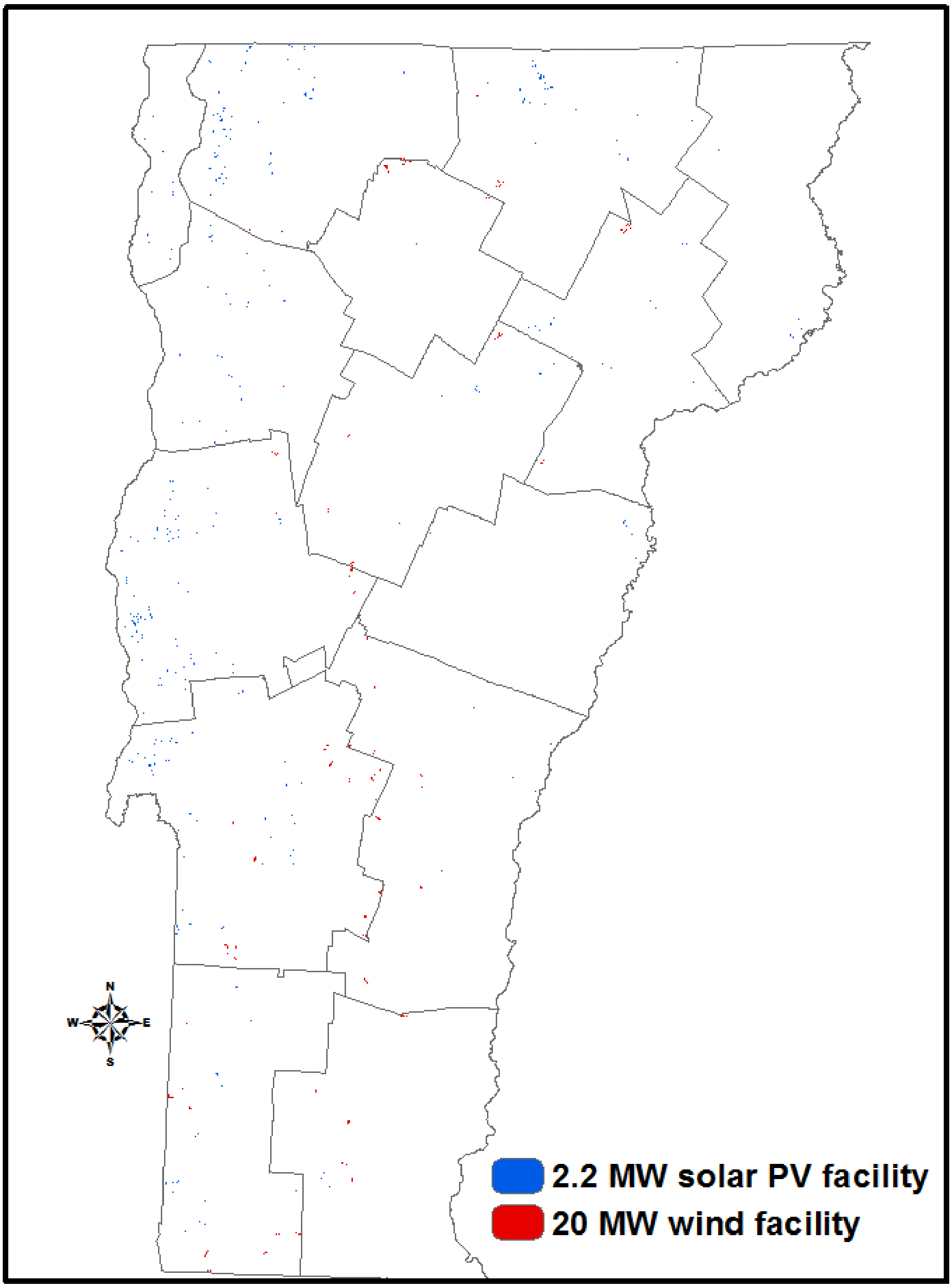


Figure 9. Simulated spatial distribution of solar photovoltaic and wind facilities for Wind Business-as-Usual scenario.

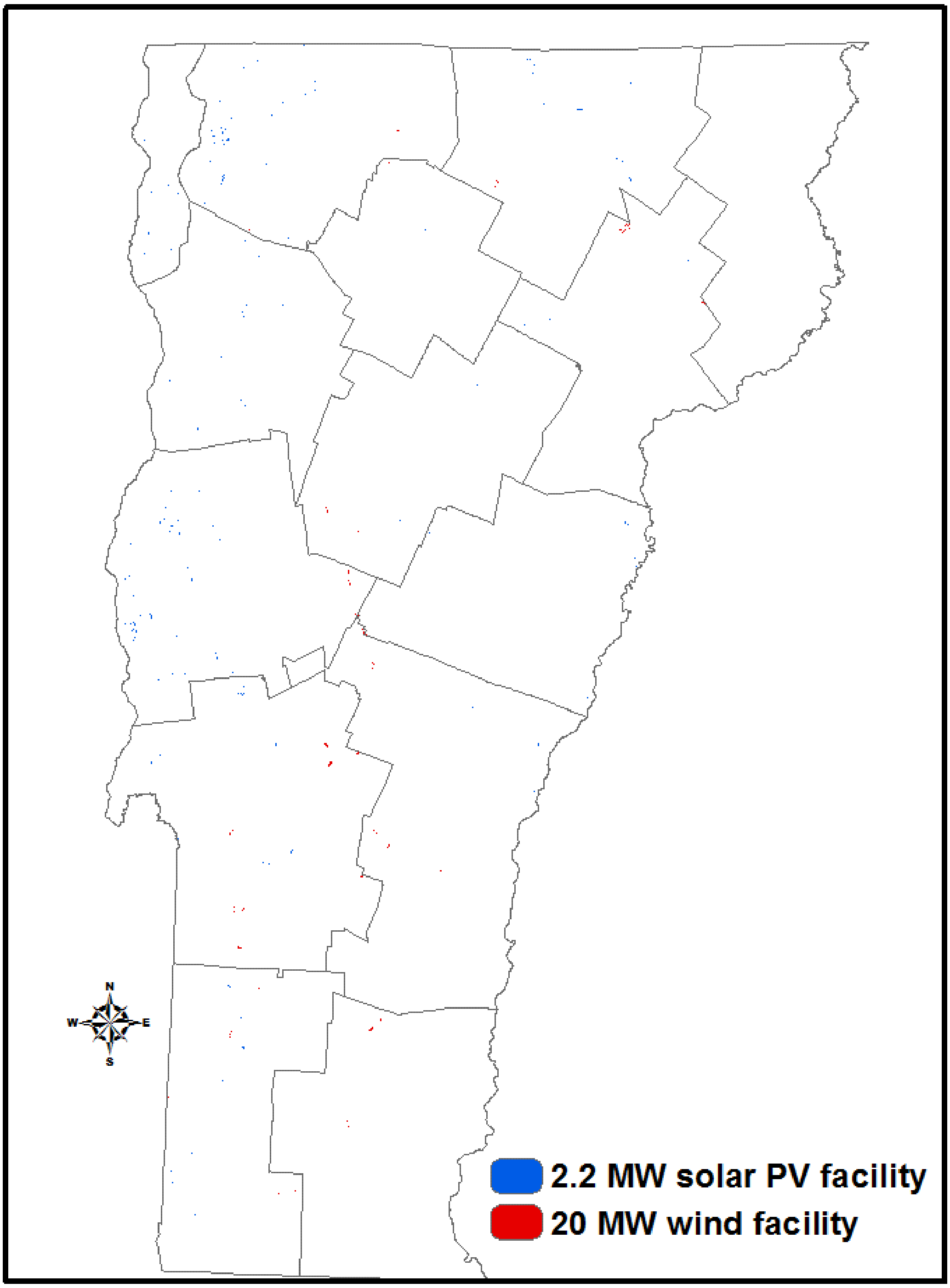
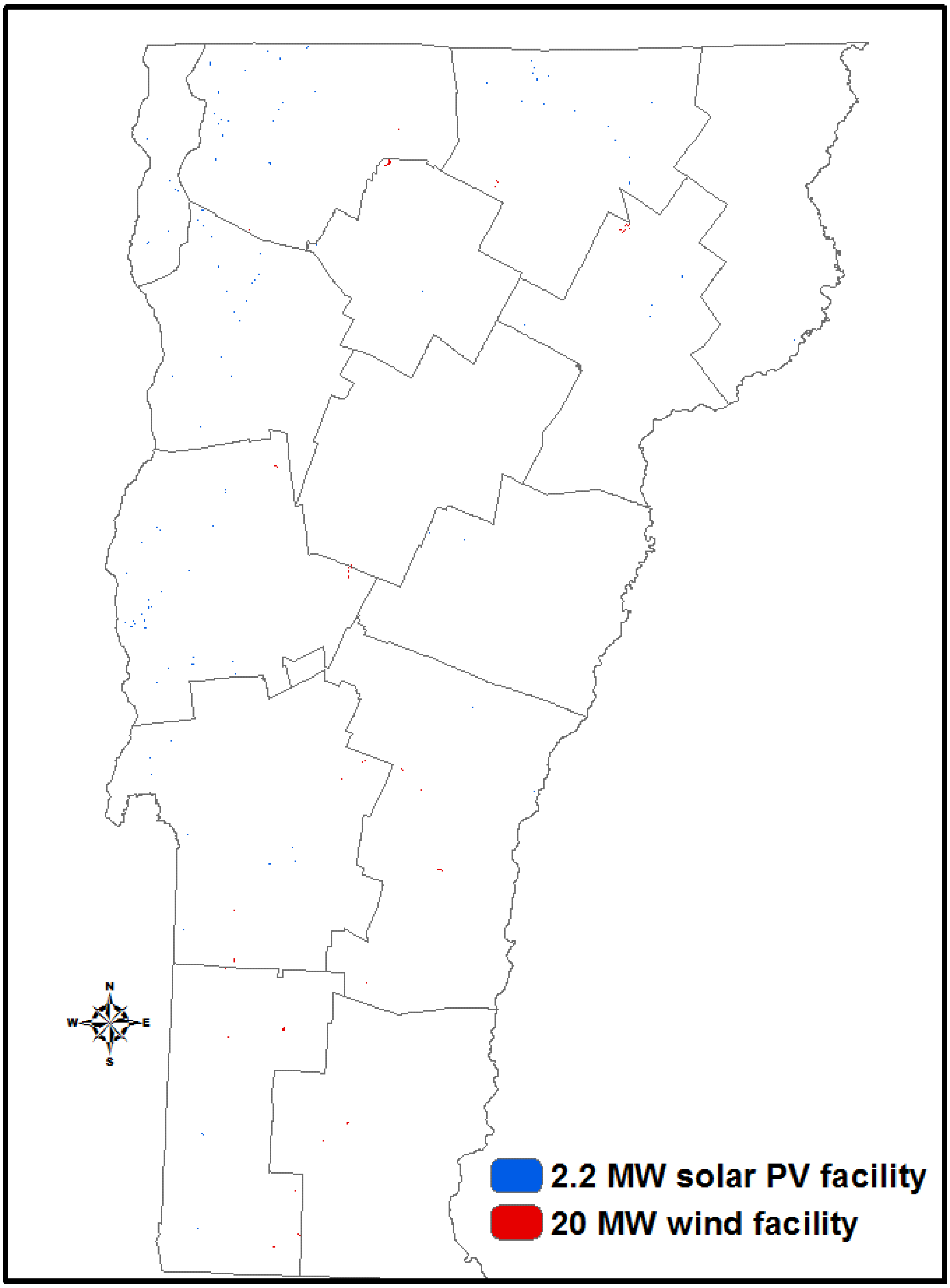


Figure 10. Simulated spatial distribution of solar photovoltaic and wind facilities for Wind Low-Electric scenario.



For Q5, I assessed potential tradeoffs between use of areas offering lower resource classes (RS5: Productivity of the system) or higher biodiversity values (O2: Ecological performance measures) when achieving the required extent of land use change. I determined the alternative pathways for achieving the required amount of land area by beginning first with the most suitable land area, as defined by highest solar PV or wind resource class and lowest biodiversity value. A proportion of one or higher indicated that the land area is available using a given combination of suitable areas, but only in the aggregate. Therefore, I identified the point at which the proportion of total suitable land area available exceeded the area required by a factor of five, as a more conservative assumption that the required land area is available.

The Wind Low-Electric scenario required the fewest number of solar PV facilities of all scenarios, whereas the Solar All-Electric required the greatest. I found for solar PV resources, the amount of land area required was not available if using only the areas with greatest resource potential and lowest biodiversity (Table 2). Therefore, tradeoffs were apparent for even the Wind Low-Electric scenario. For this scenario, only 81 percent of the land area required for solar PV development was available in high resource class, low biodiversity areas. For the Solar All-Electric scenario, only 9 percent of the land area required for solar PV development was available in high resource class, low biodiversity areas. To reach the targeted amount of solar PV development for all scenarios would require that areas be selected with either lower resource productivity or higher biodiversity value, and these tradeoffs increased as number of facilities increase.

Table 2. Proportion of Solar Photovoltaic Resource Potential Available of Area Required for Given Combinations of Resource Class and Biodiversity Value.

Slope	Solar radiation ($kWh/m^2/yr$)	Biodiversity value	Proportion of potential to required land area for scenario with	
			Least land required (Wind-LE)	Most land required (Solar-AE)
0 – 4%	1400 - 1600	Low	0.81	0.09
0 – 4%	1200 – 1600	Low	16.17	1.89
0 – 4%	1400 - 1600	Low to moderate	9.94	1.16

The Solar Low-Electric scenario required the lowest number of wind power facilities of all scenarios, whereas the Wind All-Electric scenario required the greatest. When limited to use of only low biodiversity areas in the Solar Low-Electric scenario, I calculated that the required land area for wind power development was potentially available with only low biodiversity areas only if using the lowest wind resource class (Table 3). Alternatively, the sufficient land area could be achieved by using the combination of highest wind resource potential and low to moderate biodiversity value. Therefore a tradeoff appeared to exist even at this lowest level of wind power development. I found no further significant increase in available land area without combining lower resource potential and moderate to high biodiversity value. For the Wind All-Electric scenario, only a combination of lower resource class and moderate or high biodiversity value allowed sufficient land area.

Table 3. Proportion of Wind Resource Potential Available of Area Required for Given Combinations of Resource Class and Biodiversity Value

Wind speed (m/s) and biodiversity value	Proportion of potential to required land area for scenario with	
	Least land required (Solar-LE)	Most land required (Wind-AE)
8.2 – 10.7 and low	0.00	0.00
7.4 – 10.7 and low	0.01	0.00
7.0 – 10.7and low	0.19	0.02
6.5 – 10.7 and low	2.42	0.28
8.2 – 10.7 and low to moderate	11.47	1.34
7.4 – 10.7 and low or 8.2 – 10.7 and moderate	11.47	1.34
7.0 – 10.7 and low or 8.2 – 10.7 moderate	11.65	1.36
7.4 – 10.7 and low to moderate	49.86	5.82
7.4 – 10.7 and low or 8.2 – 10.7 and moderate to high	17.35	2.03

These findings supported the Q5 hypothesis that tradeoffs become apparent between resource productivity and biodiversity with even small increases in LUCC due to development of facilities. Tradeoffs between use of lower resource potential and moderate to high biodiversity value became apparent as transitions increased with higher development scenarios, yet for both solar PV and wind power development, I found that even the lowest levels of development would require confronting a tradeoff between lower resource potential and moderate biodiversity value. That is to say I found that the most suitable land area was insufficient for meeting the amount required for both solar PV and wind development under all scenarios. For solar PV, areas with moderate biodiversity could likely be avoided in all scenarios except the Solar All-Electric scenario, whereas with wind power, areas with moderate biodiversity were likely to be required for all scenarios except the Solar Low-Electric scenario. This suggested a further tradeoff between choice of technologies, importance of resource and expected impact to biodiversity.

The key findings of this chapter can then be summarized as follows:

1. Depending upon the importance of the renewable electricity resource and choice of the technology used, **Vermont will require from 178 to 1,527 - 2.2 MW solar PV facilities and an additional 9 to 76 - 20 MW wind facilities by 2032.**
2. **Vermont's solar PV resource potential is equivalent to 18.9 percent of the state's total land area, and wind resource potential is equivalent to 3.1 percent of the state's total land area.** The distribution of both solar and wind resource potential varies from county to county.
3. **Sufficient resource potential is available in Vermont for achieving the goals of Act 170 for all scenarios.** All counties offer solar resource potential, and most offer wind resource potential.
4. **Concentrations of suitable areas exist in the Champlain Valley for solar PV development and along the ridgeline of the Green Mountains for wind power development.**
5. **LUCC simulations can produce plausible development patterns of solar PV and wind facilities for Vermont.** The two All-Electric scenarios appear to produce distinctly different spatial patterns as compared to all other scenarios due to the higher number of facilities required.

Renewable electricity development in Vermont, as assessed here, will require confronting a tradeoff between use of areas with either lower resource potential or moderate biodiversity value at even the lowest levels of development, because the most suitable land area is insufficient for supplying the area required under all scenarios. **Areas with moderate biodiversity can likely be more easily avoided with solar PV development than wind power development.**

2.1. Interpretation of Results

Several elements of Vermont's renewable energy SES appear to be critical. Social or ecological performance is a function of the number of facilities. The simulated development patterns are driven by number of facilities, which is based on importance of electricity to end-use consumers (consumption patterns/conservation), sectoral boundaries (transportation/heating), resource policy, productivity of resource (capacity factor), technology (productivity improvements), and characteristics of human-constructed facilities (factors influencing the size of large-scale facilities). Critical factors of Vermont's SES for social and ecological outcomes include the definition of sector boundaries, the size of the resource system defined as areal extent of resource potential, the chosen technology and the spatial distribution of the resource potential.

In consideration of the number of facilities required to meet the state's policy goals (Q1), any scenario will require many more facilities by 2032 than currently exist in Vermont, and require considerably more land area. The number of facilities and resulting land area requirements vary greatly depending on the electricity supply portfolio and level of importance of electricity to end-users. Either All-Electric scenario will require increased electricity consumption above projections of current levels, and therefore will require the greatest land use. The Solar All-Electric scenario requires more than double the land area than Wind All-Electric scenario. Much greater reductions in retail sales than the percentage used in the Low-Electricity scenarios appear to be required if meaningful reductions in number of facilities and land use are desired. Because the capacity factors selected reflect conservative regional estimates, the number of facilities can be understood as high end estimates for each scenario.

Nearly one-fifth of Vermont's land area is in solar PV resource potential, whereas approximately 3 percent is in wind resource potential (Q2). Adequate resource potential exists within Vermont for reaching the state's policy goals (Q3).

Considering suitable locations and potential development patterns, statewide distribution is possible and concentrations of suitable locations are available for large-scale renewable electricity development in Vermont. Development of large-scale solar PV facilities can be suitably sited throughout the state with concentrations within the Champlain Valley, while large-scale wind facilities are best concentrated along the ridgeline of the Green Mountains (Q4). Preferences for either solar PV or wind power facilities produce different land use patterns, in generally different areas of the state. The number of users/facilities directly affects spatial land use patterns.

Tradeoffs between resource productivity and biodiversity value will arise at all scales of RE development (Q5). The most suitable land area is insufficient for meeting the amount required for both solar PV and wind development under all scenarios. Solar PV will require much more land than wind power, but will offer more opportunity to avoid impacts to biodiversity per facility. For solar PV, areas with moderate biodiversity can likely be avoided in all scenarios except the Solar All-Electric scenario, whereas with wind power, areas with moderate biodiversity are likely to be required for development for all scenarios except the Solar Low-Electric scenario. This suggests a further tradeoff between choice of technologies, importance of resource and expected impact to biodiversity. Solar PV facility development can mitigate impacts to biodiversity by careful selection of siting, whereas wind development can mitigate impacts by careful multi-use management practices.

2.1. Implications and Limitations of Research

Vermont's total land area approaches 2.4 million hectares. The total area of farmland in Vermont includes an estimated 500 thousand hectares [18], while Vermont's urban landscape accounts for approximately 40 thousand hectares [19]. For perspective, the three 30-percent-solar scenarios would require the equivalent of 1 - 2 percent of Vermont farmland, or 8 – 23 percent of urban land. The Solar All-Electric scenario requires nearly 10 thousand hectares, or over 37 square miles of facility development, roughly equivalent to the land area of the towns of Peru or East Haven, Vermont, whereas the Wind All-Electric scenario requires nearly 4.5 thousand hectares or 17 square miles for development of facilities, roughly equivalent to the land area of the town of Isle La Motte, Vermont. For comparison, Vermont's 18 ski resorts include a total skiable area of just under 2.5 thousand hectares [20]. With 242 towns in Vermont, the by 2032 the state requires the equivalent of 1 to 6 – 2.2

MW solar PV facilities per town, and 1 – 20 MW wind facility for every 3 to 27 towns. While clearly a substantial increase in development of facilities, the ability to plan for these developments would appear to be within the capacity of towns and regional planning commissions as with planned developments currently. The time span of 20 – 30 years does not account for systems commissioning and decommissioning. Although relatively few facilities are now in use, turnover will become a greater issue going forward and will require long-term thinking for consideration of an on-going pattern of in-state commissioning and decommissioning rather than a continued reliance on imports as done now. Additionally, at an expected 20 to 30 – year facility lifespan, towns and regions can anticipate repeated opportunities to consider, adopt and modify these deliberation processes over time, as individual facilities are both newly proposed and ultimately decommissioned.

I include here only a single transition, from present patterns to 2032 projections. Understanding of the SES might benefit from multi-phase transitions, at least reflecting the policy goal for 2017 and 2050. Spatial constraints appear less critical than temporal limitations given the timeframe of Vermont's energy policy goals. For the years 2015 to 2032, the resulting number of facilities required translates into 10 to 85 solar PV facilities and one-half to four wind facilities to be constructed annually (Table 4). For solar PV facilities this rate is the equivalent of one to seven facilities per month for the given time period.

Table 4. Quantity of Solar Photovoltaic and Wind Facilities to be Constructed Annually per Scenario, 2015-2032.

Scenario	2.2 MW solar PV facilities	20 MW wind facilities
Solar-AE	84.8	1.4
Solar-BAU	34.9	0.6
Solar-LE	29.7	0.5
Wind-AE	28.3	4.2
Wind-BAU	11.6	1.7
Wind-LE	9.9	1.5

Given this pace of deployment, the solar scenarios seem unlikely and only the Wind-BAU or Wind-LE scenarios appear within reach. Even here, at roughly one solar PV facility per month and one wind facility every 18 months, a significant leap in the pace of project completion is required, which points to the importance of SES elements such as deliberation processes, knowledge of the SES and investment activities. To be within reach under the terms of Act 170, the scenarios then could target even lower levels of retail electric sales, which would require further conservation and efficiency measures, in effect reducing the importance of the resource to users. Alternatively, the proportions of wind and solar, in particular, could be reduced and this generation replaced with other nonrenewable technologies such as hydroelectricity or biomass. With these technologies, a different set of social and ecological impacts can be anticipated.

More likely perhaps is that Vermont will require a longer timeframe to reach these levels of renewable electricity development. Future policy could then target a higher proportion of renewables for electricity as part of the state's long-term goals beyond 2032. Current consumption trends appear to track the All-Electric retail sales levels, yet do not yet account for any significant shift of use from transportation and heating, significant increases due to the installation and maintenance of new facilities and transmission systems, or population increases. Therefore future policy might need to anticipate even higher electricity demand than All-Electric projections. Because the development of a large number of renewable resource facilities requires a major investment within next twenty years, it does not seem justifiable to invest in further development of nonrenewable systems or pursue portfolio standards, incentives, etc. that include significant percentages of fossil-fuel sources for electricity generation.

The resulting number of facilities would vary by making different assumptions about the amount of heating and transportation that shifts to use of electricity, the extent of conservation or efficiency reductions, the potential to substitute solar PV and wind with other renewable sources, and selection of capacity factor. Additionally, a 6 hectare - 2.2 MW solar PV or 17 hectare - 20 MW wind facility might be smaller than desirable, whereas by clustering development into larger patches, efficiencies of scale could be discovered, although at risk of reducing the number of possible siting locations and sacrificing a widely distributed system of facilities. Solar PV might prove more desirable to develop as larger facilities due to the larger area and wider distribution of solar resource potential. If technological and storage capacity innovations proceed rapidly over the next 15-20 years then fewer facilities and less land area could be required for the same output. Likewise if small, distributed systems can scale rapidly then these systems could offset a proportion of the large-scale generation required, yet at risk of inefficiencies of scale and lost investment potential for larger systems.

Vermont appears to offer significant solar PV and wind resource potential widely distributed across the state. Addison, Franklin and Orleans Counties together account for one-third of Vermont's large-scale solar PV resource potential, which otherwise appears to be well distributed throughout Vermont counties. Rutland, Bennington, Windham and Windsor Counties together account for roughly half of Vermont's total commercial-scale wind resource potential. The goal to locate facilities in a manner that is distributed across the state's electric grid is feasible particularly for solar PV. Due to the relative distribution, solar PV resources may be connected with lower cost than wind resources to higher population densities and existing roadways, railroad right-of-ways and transmission systems.

The results further suggest that Vermont offers sufficient resource potential to accommodate the number of facilities required. For stakeholders and decision makers in Vermont, this finding implies that the goals of Act 170 are supported by in-state solar PV and wind resource potential. An opportunity therefore exists to significantly scale up large-scale solar PV and wind power development and further reduce reliance on imported and nonrenewable sources in all sectors.

Although the resulting aggregated potential area does not account for minimum facility footprints, it appears that every county offers significant potential for solar PV resources as compared to the amount required for all scenarios. With the exception of Grand Isle County, the results similarly suggest that every county offers significant potential for wind resource potential when compared to the amount required for all scenarios.

Aggregating resource potential raises uncertainty regarding the actual potential available to large-scale facilities that require a minimum land area. However the LUCC simulation was able to identify the required number of patches of the size specified for even the highest use scenarios, which might very well be beyond Vermont’s ability to develop within the timeframe available.

Possibly a more meaningful limitation involves the quality of the resource potential. Solar PV and wind development will require that site specific issues such as shading and resource class be investigated more closely. Whether issues of quality would dramatically reduce the productivity or distribution of resource potential remains unclear. Alternatively, the masking used for data layers may have overly constrained resource potential, particularly in the case of ground-mounted solar PV facilities that could be developed on previously developed sites. The effect of changing climate patterns on resource potential also remains a potentially important but uncertain variable.

This comparison suggests that the resource potential offers substantially more land area than that required for facilities development, and therefore can support the desired scale of development as originally hypothesized. Any of the above issues affecting either the number of facilities required or the size of in-state resource potential could prompt a reassessment of this finding.

Suitable sites as defined by both higher resource potential and lower biodiversity value are found statewide for solar PV, including some concentrations in the Champlain Valley, and concentrated along the Green Mountains for wind. Despite the risk of overlap of ecological attributes between the resource potential and biodiversity data sets, I observe a distinct gradation of biodiversity values, which implies that the two sets of data do not entirely correspond. A more comprehensive assessment of suitability would require consideration of additional factors such as distance to key features, existing and proposed siting rules, land use development patterns, specific biodiversity contributions and local community needs.

Suitability can be used to define probable locations for facility development. Probabilities as defined reflect the judgment of the researcher. In this case I elected to apply a steep range of probability values to biodiversity and an incremental, narrow range of values to classes of potential. This choice reflects the assumption that differences in resource class will influence site selection to a much lesser degree than differences in biodiversity value. Given the assigned probabilities, I observe distinct spatial transitions by varying parameters across the six scenarios, as hypothesized. In addition to the resource potential and biodiversity values, the number of users or facilities, as influenced by the level of resource importance and the technology used, strongly affects the resulting spatial land use pattern.

Each simulation represents a plausible pattern of development of facilities by 2032. A visual representation of these development patterns can help stakeholders and decision makers understand the spatial implications of the state’s energy policy goals. All scenarios achieved the desired level of facilities development. The limitations affecting number of facilities, size, distribution and quality of resource potential, and biodiversity values apply here as well.

As defined in these scenarios, it appears that the choice to shift transportation and heating to electricity would urge a more intensive pattern of land use development, while small reductions in use minimally influence the statewide pattern, although localized effects can also be important. A closer analysis is required to determine the significance of this distinction, especially between the Solar

Business-as-Usual (Figure 6) and the Solar All-Electric scenario (Figure 5). The results of the LUCC simulations suggest that observed distinctions become less relevant as the difference between numbers of facilities narrows.

Because of the concentrations of more suitable locations, as level of resource use increases sharply from the BAU to the All-Electric scenarios, land use transitions are likely to concentrate accordingly if resource potential and biodiversity are the overarching concerns for siting. This result implies that a conflict may arise between site-specific attributes of suitability and the state's intention to distribute rather than cluster development of facilities. While wind scenarios require comparatively fewer total facilities and developed acres than solar PV, the land use pattern generally favors a less distributed pattern.

A potential response to clustered patterns of development might be to create operational rules that ensure that the benefits of renewable electricity are returned to those communities most directly affected by the burdens of land use development, perhaps in the form of payments from end users to community organizations. Property-rights systems and the associated benefits of ownership also become relevant if the benefits of development are not perceived to be shared fairly. This issue may be less important when development patterns allow for facilities to be located closer to end users, but in the case of the wind scenarios, the development patterns appear to concentrate further from the population densities of the Champlain Valley.

Large-scale solar PV and wind appear to be complementary resource systems in terms of land area and site selection requirements, and overall distribution of development when the two systems are used together. The research does not account for the additional development of biomass and hydroelectric facilities or the transmission and distribution system. Including these elements would provide a more comprehensive understanding of the implications of the electricity portfolios as defined here, including the overall compatibility of these different technologies. The effect on land use transitions of development of larger facilities or patch sizes remains uncertain. Additionally, by default the patching function prioritizes to some degree the transition of nearest neighbor cells, which might then exaggerate the clustering of development patterns around areas with existing facilities. Given the same probabilities, the effect of an existing facility remains unclear, as to whether its presence would favor further development due to increased technical expertise, social norms, leadership, supporting infrastructure, etc., or inhibit further development due to local saturation, for example.

A tradeoff between resource productivity and biodiversity becomes apparent at all scales of development of generating facilities because the land area of the most suitable sites is insufficient for supplying the area needed. Therefore the need to confront this tradeoff exists at even lower levels of renewable electricity development and increases with higher levels of development. Understanding the quality of this tradeoff requires a closer consideration of the classes of resource potential and tiers of biodiversity contribution.

For solar PV facilities, the tradeoff at the lowest level of solar PV development involves the choice of sites with either moderate biodiversity value or reduced solar radiation from a minimum of 1400 kWh/m2/year down to 1200 kWh/m2/year. Either of these choices appears to offer sufficient land area for solar PV in the Wind Low-Electric scenario. The Solar All-Electric scenario would simultaneously require further reductions in resource class and increased displacement of higher biodiversity values.

For wind power facilities, the tradeoff at the lowest level of wind development concerns choosing sites with either moderate contributions to biodiversity or reduced wind speeds from a minimum of 8.2

m/s down to 6.5 m/s. Because resource potential is aggregated here, wind development that uses areas of moderate biodiversity value might be unavoidable. The Wind All-Electric scenario likewise appears to require the use of areas with both wind speeds of 7.0 – 7.4 m/s and moderate biodiversity value.

The tiered contribution to biodiversity data set masks the underlying biodiversity components in favor of an aggregated and weighted score or value. Rare species and natural communities are systematically assigned to the greatest contribution to biodiversity tier. Other terrestrial biodiversity components that received larger weights include rare physical landscapes, habitat blocks, and connecting lands smaller than 2,000 acres (809 hectares). Due to the co-occurrence approach used for scoring cells in BioFinder data, the association between these additional components and any specific location cannot be determined. However, some generalizations can be made. None of the scenarios appear to require areas with high, very high or greatest contributions to biodiversity. Therefore solar PV and wind power development can proceed while avoiding impacts to rare species and natural communities in Vermont, and might additionally avoid impacts to rare physical landscapes, habitat blocks, and connecting lands, although presently this determination requires a site-specific assessment.

At the other end of the biodiversity value scale, areas with negligible biodiversity contribution might be available but due to data uncertainties have been excluded from the suitability layers. Relevant terrestrial areas with low biodiversity contributions include grasslands and shrublands, representative physical landscapes, connecting blocks and anchor blocks 2,000 acres or larger, common natural communities and mast production areas. Development of solar PV and wind power facilities appears likely to require these types of natural areas even at lower levels of development.

Therefore it is worth considering how to mitigate effects upon grasslands and shrublands, representative physical landscapes, connecting blocks and anchor blocks, common natural communities and mast production areas with management practices that allow for co-occurrence of facilities and restoration following decommissioning. In the case of solar PV, this approach may largely involve careful site selection of the most compatible of these types of natural areas or avoiding natural areas entirely wherever possible. Shared management plans of agricultural lands for large-scale solar PV facilities can offer potential for multiple uses such as small livestock grazing and grassland bird habitat [21]. Urban and developed areas can be considered to support infill and combined residential and energy development planning, with proximity to end users. The U.S. Environmental Protection Agency is encouraging renewable energy development on current and formerly contaminated lands, landfills, and mine sites [22]. By integrating RE development with local and regional land use and development patterns, facilities can be clustered around existing development, or conversely new- or re-development can be clustered around areas with resource potential, especially for solar PV. At this scale of development, state and local planners might benefit from an understanding of the size or density of facilities needed to justify developing the future transmission and distribution system around suitable locations for facilities, rather than the other way around. This issue might be more relevant for solar PV development than wind due to the wider distribution of solar PV potential.

Wind power development in Vermont is likely to require higher elevation forests, which can offer multiple use management. Recommended wind siting practices of the National Regulatory Research Institute include approaches for regulating noise impacts using decibel measures and flicker impacts using limits of duration, avoiding wildlife and habitat exclusion and buffer zones, avoiding special cultural or anthropological lands and scenic vistas, and minimizing interference with existing towers or infrastructure [23]. Priority energy siting guidelines of the Vermont Agency of Natural Resources consider wildlife and wetland habitat and connectivity, rare and irreplaceable natural areas, endangered species, riparian buffers, groundwater impacts during construction, bird and bat mortality, and high elevations. Additionally it has been recommended that the Vermont Agency of Agriculture, Food and Markets become a party in the siting process in consideration of impacts to prime and statewide agricultural soils [24].

Because each facility requires a minimum patch of land area, suitable land might be available according to the resource potential, but in patches too small to accommodate the development of a large-scale facility. As with the LUCC simulation, patches smaller than the footprint of the facility would need to be excluded, as would other areas deemed unsuitable for other reasons such as distance to transmission or distribution systems.

The relationship between incremental reductions in resource class and productivity of the system might be important to clarify for future research. The capacity factors selected reflect conservative estimates in that the values are associated with lower resource classes. The effects of changing climate patterns on resource class remains uncertain, although based on projections of increased precipitation and more storm events, Site selection of areas with most suitable resource class, for example greatest solar radiation or highest wind speeds, can be expected to increase the annual productive output of these technologies. This increase would have the effect of reducing the number of facilities required from the amounts calculated here. Therefore it is reasonable to expect that as more sites with lower resource classes are selected, then the number of facilities required will more closely approximate the number calculated.

This expected outcome implies that all levels of development require confronting a tradeoff between the selection of sites with higher resource classes, which therefore reduces the total number of facilities and land area required, or sites with low biodiversity value, which avoid impacts to rare physical landscapes, habitat blocks, and connecting lands. In other words, the choice involves developing either less land overall but displacing more valuable biodiversity, or developing more land overall but displacing less valuable biodiversity.

As with any tradeoff, neither choice offers a clear advantage, but it is clear that as levels of development increase, the choices progressively involve developing more land area in addition to displacing more valuable biodiversity. Alternatively, by reducing the importance of the resource, development patterns can allow siting of facilities in the most suitable locations, meaning those areas with the highest resource class and lowest contributions to biodiversity. A more ideal outcome would then involve shifting transportation and heating to renewable electricity even while reducing the total retail sales from current levels. Conservation strategies can potentially improve the productivity of these systems while also decreases displacement of valuable biodiversity. While the state has identified energy efficiency and conservation as priority goals, future policy might specify not just a percentage of renewables but also a level of development or resource importance that reduces the need to confront this tradeoff.

3. Experimental Section

I developed two electricity mix portfolios as informed by existing stakeholder input and materials [25-26]. The solar portfolio assumes 30 percent solar PV electric and 10 percent wind power, while the wind portfolio reverses these proportions. Hydropower and biomass generation were held constant for both portfolios, while the percentage of wind and solar were varied. Both portfolios therefore include: 25 percent of supply purchased by Vermont utilities through the regional electric market for in-state distribution, and including nonrenewable sources; 25 percent provided through hydropower, either in-state or out-of-state; 10 percent provided through biomass systems; and the remaining 40 percent provided through in-state solar PV or wind power generation. This remaining 40 percent was then varied to allow for comparison between alternative solar- and wind-based renewable energy systems.

I then collected data on projections for net generation and retail electric sales through 2032 and beyond to develop three levels of renewable energy generation targets. To project electricity demand (i.e. retail electric sales) for Vermont in 2032, I first determined an average ratio of retail electric sales to net generation of 0.86, meaning that about 86 percent of net electricity generation is available for retail sales. Facilities provide electricity directly to utilities or into power markets on a wholesale basis [27] and therefore achieve levels of net electricity generation beyond that which is sold through retail markets. I applied this factor to the average net generation of electric power for 2010-2012, the most recent years for which data are available [3], to find estimated total retail electric sales for 2012 of 5.80 million MWh. This estimated total retail electric sales was used as the baseline for all three estimates and projected out to 2032.

The Business-as-Usual (BAU) estimate was based on the projected electricity consumption for 2032 as described in the Comprehensive Energy Plan [1]. The Comprehensive Energy Plan borrows the forecast for Vermont electric consumption from the Vermont Electric Company, which projects an average annual electric use increase of 0.4 percent through 2030, accounting for program efficiency savings. The BAU estimate adopted this average annual electric use increase of 0.4 percent to yield a BAU estimate of total electric retail sales for Vermont of 6.28 million MWh in 2032.

A Low-Electric (LE) estimate assumed deeper cuts in projected electricity consumption due to efficiency and conservation savings, and limited electrification of the transportation and thermal energy sectors. The LE target therefore projected an average annual electric use decrease of 0.4 percent to arrive at an LE estimate of total electric retail sales for Vermont of 5.35 million MWh in 2032.

An All-Electric (AE) estimate assumed the projection of the Vermont Public Service Board. The Vermont Public Service Board projects an increase in the overall demand for electricity due to the electrification of the transportation sector and a greater use of electric air- and ground-source heat pumps for both heating and cooling [24]. Accounting for these increases, various stakeholder groups have more recently projected a total average annual electric use of three times the 2011 level, or approximately 18.0 million MWh for 2050 [28]. I calculated the AE estimate, beginning with the same 2012 baseline and assuming a linear trend to a 2050 total demand of 18.0 million MWh, to find the 2032 estimate of total electric retail sales for Vermont at 15.27 million MWh.

Based on this range of projected levels of demand, Vermont retail sales must reach between 4.01 and 11.45 million MWh of annual renewably-sourced electricity by January 1, 2032. Assuming a constant ratio of total electric sales to net generation, I then converted the retail sales projections to net generation required for all renewable electricity facilities. By 2032 renewable electric facilities serving Vermont will annually generate a low-end targeted 4.64 million MWh and a high-end targeted 13.24 million MWh to reach the goal of Act 170. I defined these two extremes as the Low-Electric and All-Electric renewable electricity generation targets for 2032 (Table 5).

Table 5. Net Renewable Electricity Generation Targets, Benchmark Years

Year	% net renewable electricity generation	Net renewable electricity generation (million MWh)		
		Low-Electric target	Business-as-Usual target	All-Electric target
2012	25	1.68	1.68	1.68
2017	50	3.29	3.42	4.72
2032	75	4.64	5.45	13.24

A renewable electricity generation target was determined for each renewable electricity source for 2032 (Table 6) by applying the percentages defined within the solar PV and wind technology portfolios. Pairing both the solar PV and wind power portfolios with each of the three renewable energy generation targets then yielded six distinct scenarios.

Table 6. Net Renewable Electricity Generation Required for Each Source by Target and Portfolio, 2032

Electricity source and target	Net generation million MWh (percentage)	
	Solar portfolio	Wind portfolio
Hydroelectric		
All-Electric	3.31 (25)	3.31 (25)
BAU	1.36 (25)	1.36 (25)
Low-Electric	1.16 (25)	1.16 (25)
Wind		

Electricity source and target	Net generation million MWh (percentage)	
	Solar portfolio	Wind portfolio
All-Electric	1.32 (10)	3.97 (30)
BAU	0.54 (10)	1.63 (30)
Low-Electric	0.46 (10)	1.39 (30)
Biomass		
All-Electric	1.32 (10)	1.32 (10)
BAU	0.54 (10)	0.54 (10)
Low-Electric	0.46 (10)	0.46 (10)
Solar photovoltaic		
All-Electric	3.97 (30)	1.32 (10)
BAU	1.63 (30)	0.54 (10)
Low-Electric	1.39 (30)	0.46 (10)
Regional market		
All-Electric	3.31 (25)	3.31 (25)
BAU	1.36 (25)	1.36 (25)
Low-Electric	1.16 (25)	1.16 (25)

I used data on existing and planned large-scale solar PV and wind facilities to operationalize size of facilities defined by nameplate capacity. Several utility-scale solar PV generation facilities measure approximately 2.2 MW in generating capacity [29-30] due to this being the minimum cut off for expedited permitting for Vermont’s Sustainably Priced Energy Development (SPEED) Program, enacted by the Vermont Legislature to promote the development of in-state RE suppliers [31]. Additionally, the proposed Simplified Tier system for project review classifies the Standard Process (Tier 3) at a range of 2.2 to 15 MW nameplate capacity [24]. Therefore, I assumed a 2.2 MW solar generation facility. Based on averages of existing facilities, I also assumed a minimum utility-scale wind generation facility as a project of 20 MW in nameplate generating capacity [27].

To determine the annual generating capacity per facility for solar PV and wind (Table 7), I applied a capacity factor of 13.5 percent for ground-mounted solar PV in Vermont and 30 percent for large-scale wind power with turbine elevations above 70 m [29].

Table 7. Solar Photovoltaic and Wind Facility by Nameplate, Capacity Factor and Annual Power Generation

Facility	Nameplate capacity (MW)	Capacity factor	Annual generation (million MWh)
Solar photovoltaic	2.2	0.135	0.0026
Wind	20.0	0.300	0.0526

I operationalized the land area footprint of a solar PV and wind facility based on the average footprint area per MW of existing and proposed facilities in Vermont (Table 8) [32]. For a 2.2 MW solar PV facility, I calculated a 6.04 hectare footprint per facility. For a 20 MW wind power facility, I calculate a 17.49 hectare footprint per facility. I was then able to calculate the number of facilities required for each technology under all six supply portfolios (Q1).

Table 8. Land Area per Megawatt and per Facility for Solar Photovoltaic and Wind Facilities

Facility	Average area per MW (hectares)	Area per facility (hectares)	Area per facility (acres)
Solar photovoltaic (2.2 MW)	2.74	6.04	14.91
Wind (20 MW)	0.87	17.49	43.21

Land use impacts can be understood and simulated using spatial or geographic information systems and environmental modeling platforms. Here I use Dinamica EGO 2.2.8 [33], an open source environmental modeling platform that has been applied by researchers and professionals to various spatial modeling studies, including those in support of sustainable land management, planning and policy [34-37]. Through the Vermont Center for Geographic Information [38], I retrieved the statewide Vermont boundary data layer (BoundaryOther_BNDHASH) and extracted the shapefile set of files. A shapefile is a digital vector storage format for storing geometric data types of points, lines and polygons, and associated attribute information. The BNDHASH data layer includes feature classes for Vermont state boundaries, villages, towns, counties, Regional Planning Commissions, and Local Emergency Planning Committee boundaries. The master BNDHASH layer is managed as an ESRI geodatabase feature dataset by the Vermont Center for Geographic Information. Using the Polygon to Raster conversion tool in ESRI ArcGIS ArcMap 10.2, I converted the statewide Vermont layer (Boundary_BNDHASH_region_vtband) and the Vermont county layer (Boundary_BNDHASH_region_counties) shapefile sets to raster files.

I prepared the biodiversity and resource potential data for use in Dinamica. I retrieved the BioFinder Tiered Contribution to Biodiversity layer (EcologicOther_BIOFINDER) [39] from the Vermont Center for Geographic Information. The BIOFINDER layer is a raster digital data layer published by the Vermont Agency of Natural Resources in 2013. The Tiered Contribution to Biodiversity represents the result of a weighted sum of 21 component datasets. The BioFinder layer attributes include the weighted sum value, the raster cell count, area in acres, and the six classes of tiers.

I then retrieved the map layers for solar and wind potential (EnvironOther_SOLAR, EnvironOther_WIND) published for use with the Vermont Sustainable Jobs Fund’s Renewable Energy Atlas of Vermont. From the solar potential layers, I selected the layer for ground based sites (Environ_Solar_poly_AreaPV) indicating ground-mounted solar PV potential in Vermont [29]. The attributes of the Potential Solar Area (Ground Based) Sites dataset are identified by each represented polygon’s internal feature number, and include feature number, shape, area, perimeter, soil designation and solar radiation-slope union class. To these attributes, I created a new attribute field to categorize polygons according to solar radiation-slope class union attribute to allow for reclassification of solar PV resource potential within this dataset.

Approximately 11 percent of polygons included in the original solar PV vector data set did not include data on solar radiation-slope class. I therefore treated these as null values to avoid overestimating available solar PV resource potential. Thus the resulting reclassified layer demonstrated a 3 to 6 percent reduction in areal extent of solar PV resource potential per county and 4 percent overall by state from the original polygon layer, representing a slightly more conservative estimate of resource potential.

Wind resource data layers are categorized according to various turbine hub heights. From the wind potential layers, I selected the layer for large commercial areas (Environ_Wind_poly_LrgCmrcl70m) [29]. The attributes of the Large-scale Commercial Wind data set include the object ID, shape, wind resource class, wind speed, distance to existing transmission lines and roads, shape length and area and key field ID. To these attributes, I created a new attribute field to categorize polygons according to wind resource class, with a value of one assigned to the highest wind resource class, and four to the lowest included within this data set. The original vector layer included wind speed data for all polygons within the data set, so no reductions were made by reclassifying attributes and converting to raster data.

To allow for the use of the solar and wind potential layers and the statewide boundary data layers in Dinamica, I converted the solar PV and wind area shapefile sets, now including new attribute fields, to raster layers using the Polygon to Raster conversion tool in ESRI ArcGIS ArcMap 10.2. I used the BioFinder layer to define the environmental variables of cell size (10 m x 10 m), processing extent and output coordinates (projection) of the new solar and wind potential raster layers. The BioFinder layer is defined by: VT State Planar Coordinate System (Meters); North American Datum 1983. In layer properties I changed the value field to select the new attribute values for each set of shapefiles. To convert each file type for use in Dinamica, I exported as .tif files the new solar and wind potential area raster layers and the BioFinder Tiered Contribution.

I then performed spatial calculations, suitability modeling and land use/land cover change (LUCC) simulation by using Dinamica [33] to build and run several original models. First, I estimated the areal extent of large-scale commercial wind and solar PV resource potential in the state of Vermont (Q2) using the wind and solar resource potential layers. I repeated this step by county using the Vermont county layer to determine how this potential land base is distributed (Q2). I calculate the land area required for facilities as a percentage of resource potential to determine whether sufficient land area is available in Vermont. (Q3).

I similarly developed models to determine the areal extent of the most suitable locations per county for solar PV and wind development as used within the LUCC simulations (Q4), and to identify possible tradeoffs between resource potential and biodiversity (Q5). Suitability maps were developed by assigning values to resource potential classes and BioFinder Tiered Contribution to Biodiversity classes. By combining these layers for both solar PV and wind resources, probabilities were defined.

As maps of suitability, these layers could then be used to calculate available land area for each combination of resource potential and biodiversity value. Beginning with areas of highest resource potential and lowest biodiversity values, I developed a series of additional models that incrementally achieved the land area required through alternative pathways that favored either higher resource potential or lower biodiversity value, up to the point where tradeoffs between resource potential and biodiversity value were apparent. By calculating the total land area available under different combinations using progressively less suitable land areas, I determined the alternative points at which the required amount of land area for development of generating facilities is achieved. These alternative land use pathways represent the options available for achieving the land area required.

To simulate plausible land use change, I created land use and land cover change (LUCC) simulation models using Dinamica to estimate the change from resource potential to development of new wind and solar PV facilities. To model the change over time, I first developed a landscape layer for the initial condition of development. A list of existing commercial-scale solar PV and wind facilities in Vermont was available using data compiled for the Siting Commission report [29]; however these data had not yet been converted to a spatial database format. Using ArcCatalog 10.2, I created a new geodatabase for this set of existing solar PV and wind facilities, again importing the BioFinder coordinate system. I then used the ArcMap 10.2 construction tool to define a polygon feature for each facility using the World Imagery with Labels and USA State Plane Zones (NAD 83) base maps for spatial reference.

The areal extent and location of four wind facilities defined the polygons for the wind existing conditions layer: Georgia Mountain Community Wind, Kingdom Community Wind, Searsburg Wind Farm and Sheffield Wind. Using the same procedure, 10 solar PV facilities defined the polygons for the solar PV existing conditions layer: Charlotte-Hinesburg Road, Clarendon, Cross Pollination 1, St. Albans Solar, Sheldon Springs, South Burlington Solar, Southern Vermont Energy Park, SunGen1 Solar, White River Junction Solar and Williamstown Solar.

For all solar PV and wind polygon features I added a new field and assigned a value of three to indicate that the given polygon represents an existing facility. I then converted the solar PV and wind site features polygon layers to a raster files as done previously, and combined with resource potential layers to allow for the LUCC simulation model to convert land uses from potential (value = 2) to facility (value = 3) based on the required land area for facilities for each scenario. To perform this operation successfully, I disabled raster map swapping. The suitability layers were used to define probabilities for the LUCC transitions, while the number of required cells to be converted was calculate based on the required number of facilities for each scenario. Additional transition parameters included the patch size as defined by the solar PV or wind facility areal footprint, and the isometery, which was set to greater aggregation for solar PV, and less aggregation for wind, due to the likely development patterns of these facilities.

4. Conclusions

Shifting to electricity for heating and transportation increases the necessity to confront tradeoffs. Some amount of detrimental direct ecological impacts are unavoidable but can be constrained to areas of low biodiversity value if site selection favors less productive locations. At these scales of development, use of the highest resource potential requires use of areas with moderate and possibly high biodiversity value, but impacts to areas of very high or greatest biodiversity do not appear to be necessary for development of facilities.

For researchers, a framework for understanding Vermont’s emerging renewable energy system as a social-ecological system facilitates systems thinking through consideration of a broad set of potentially important variables. The SES framework is also useful for linking research across inquiry and methodologies. For decision makers, the SES framework allows for consideration of the land-energy-environment nexus to support the coordination of policy goals and approaches across these policy domains. This framework can also support better integration of energy planning across end use sectors. Future research can further develop Vermont’s RE SES framework through investigation of additional critical elements using relevant methodologies to clarify relative importance and strength of relationships of variables over time.

Researchers investigating biophysical components of Vermont’s RE SES can address several important limitations of this study. The accuracy of resource potential data, especially shading of solar PV, can be improved. Solar PV potential will be improved with LIDAR data imagery. Site specific assessments can be performed to validate and improve wind resource potential. Solar PV potential in particular could be further constrained, for example by masking prime agricultural soils, or expanded to include developed land areas. Perhaps a more flexible approach would be to develop and apply entirely unmasked resource potential data based only on solar and wind characteristics and add additional layers as desired.

The LUCC simulations can be analyzed further by calculating the level of patch aggregation or cohesion and distance to features to gain perspective on the level of fragmentation of landscape across alternative LUCC simulations. The sensitivity of the simulations to the nearest neighbor patching function or other parameters can be analyzed. If supported through existing research, local saturation values can be applied or alternatively the rate of localized “seeding” can be increased. The facility footprint (patch size) and aggregation (isometry) can be varied in consideration of larger or more spatially diverse facilities.

While suitability can be used to define probable locations for facility development, suitability layers can be further refined by eliminating small patch sizes and including additional factors such as distance to key features, existing and proposed siting rules, land use development patterns, specific biodiversity contributions and local community needs. Site specific verification and analysis of sensitivity to probability values can also improve suitability layers and LUCC simulations.

The relationship of larger ecological patterns to Vermont's RE SES deserves more attention, in particular for understanding the potential impacts of climate change and pollution on productivity of solar PV and wind power systems. The effects of changing climate patterns on resource class remains uncertain, although based on projections of increased precipitation and more storm events [40]. Solar PV capacity factors may reduce while wind may improve. Existing research on the regional energy system [26] can be further developed to extend the scope of analysis beyond Vermont's boundaries through consideration of relationships to larger, nested SES's.

Researchers can also contribute through further investigation of social components, and in particular, the influence of variables of the governance system. The importance of the resource can be varied by identifying targets with greater reductions in projected retail sales or by including and shifting output to other renewable energy technologies.

Ecological performance measures can also be better understood. Disaggregating biodiversity contributions can improve suitability layers, allowing for mixed management with those types of biodiversity contributions that allow for renewable electricity generation. By then identifying the areal extent of land use for each BioFinder tier, a perspective can be gained on development patterns needed to avoid displacement of specific types of biodiversity value. An improved assessment of BioFinder Tier 6 data is needed, which would allow for inclusion of areas with negligible biodiversity value.

Several specific interactions and relationships of SES elements could yield important insights. Broadly, clarifying the relationship between energy conservation and reductions of impacts of RE development could help refine future generation targets. Similarly, research could consider the cost of increased efficiency and conservation measures with respect to costs of land use displacement. The spatial distribution of resource potential can also be related to the spatial distribution of population density.

The relationship between incremental reductions in resource class and productivity of the system is important to clarify for future research, as related to investment activities. Site selection of areas with most suitable resource class, for example greatest solar radiation or highest wind speeds, can be expected to increase the annual productive output of these technologies. This increase would have the effect of reducing the number of facilities required from the amounts calculated here, but whether investments would be increased remains unclear.

Attributes of governance system requires close consideration in relation to social performance measures such as efficiency, equity and accountability. The deliberation processes required to facilitate local-level decision making for approval and decommissioning of facilities, and possibly involvement with operations and maintenance phases, can be better understood.

With improvements, the current research can provide tools and insights to stakeholders and decision makers. Scenario development can be used to project and anticipate potential land use impacts, increase understanding of spatial relationships and knowledge of SES more generally, build social capital through social learning, and support consideration of alternatives policy goals, and might therefore be an effective method to facilitate a renewable energy transition. The suitability layers could be used to inform future commercial and residential development patterns, to cluster end-use near resource potential, and to stack complementary development or management activities.

The BioFinder and Renewable Energy Atlas tools represent a social capital asset and source of knowledge that can support social learning and planning. The knowledge of biophysical features affects the ability to develop simulations and improve facility management and resource policy. Using these available data sets as decision support tools, Vermont could develop clear policy that will facilitate the development of renewable electricity facilities in areas that minimize conflict with higher value biodiversity.

I further suggest that Vermont decision makers and stakeholders use these data and analyses to develop land-energy management guidelines and infrastructure planning rules, to refine and reconsider the state's goals for 90 percent renewable by 2050, to innovate approaches that facilitate significant scaling up of development, and to develop multi-criteria performance measurement systems that clearly integrate social and ecological outcomes.

The path to renewable energy development in Vermont will need to address potential tradeoffs. Risks of negative environmental impacts exist, and renewable electricity development will require a thoughtful and informed approach to balance multiple goals: healthy ecosystems, adequate supply, local renewable sources, distributed power facilities, etc. A greater commitment to renewable energy generation cannot then ignore the likely impacts of these decisions [41]. Effective progress toward a renewable energy future in Vermont could benefit from a deeper understanding of the relationship of such knowledge and social norms, particularly among public sector leaders, to social and ecological performance measures.

Acknowledgments

I wish to thank my exceptional thesis committee, Asim Zia, Gillian Galford and Joshua Farley. I am equally grateful for the help and support of the students, staff and faculty of the Master of Public Administration program, the Gund Institute for Ecological Economics and the Rubenstein School for Environment and Natural Resources at the University of Vermont. I also wish to express my gratitude to the UVM Graduate College for the financial support that has allowed me the opportunity to undertake and complete this work.

Conflict of Interest

The author declares no conflict of interest.

References and Notes

1. *Comprehensive Energy Plan 2011: Facts, analysis, and recommendations (Vol. 2)*; Vermont Department of Public Service: Montpelier, VT, 2011.
2. *An act relating to the Vermont energy act of 2012* (VT LEG 281076.1); Vermont Legislature. No. 170. http://www.leg.state.vt.us/docs/2012/Acts/ACT170.pdf
3. U.S. Energy Information Administration. (2014). Independent Statistics and Analysis. http://www.eia.gov/state/?sid=VT#tabs-4 (accessed January 30, 2014).

4. U.S. Energy Information Administration [Online]. http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_use/tra/use_tra_VT.html&sid=Vermont (accessed January 15, 2014).
5. U.S. Energy Information Administration (EIA) [Online]. http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_sum/html/rank_use_source.html&sid=US (accessed January 14, 2014).
6. U.S. Energy Information Administration [Online]. http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_use/res/use_res_VT.html&sid=Vermont (accessed January 15, 2014).
7. U.S. Energy Information Administration [Online]. http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_sum/html/sum_btu_totcb.html&sid=US (accessed January 16, 2014).
8. U.S. Energy Information Administration [Online]. http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_use/eu/use_eu_VT.html&sid=Vermont (accessed January 16, 2014).
9. *Monthly energy review (December 2013, DOE/EIA-0035(2013/12);* U.S. Energy Information Administration: Washington, DC, 2013. http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf
10. State Electricity Profiles – Vermont; U.S. Energy Information Administration. 2013. http://www.eia.gov/electricity/state/ (accessed October 19, 2013).
11. *Comprehensive Energy Plan 2011: Vermont's energy future (Vol. 1)*; Vermont Department of Public Service: Montpelier, VT, 2011.
12. E. Ostrom. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science*. **2009**, *325*, 5939, 419–422.
13. E. Ostrom. A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences*. **2007**, 104, 39, 15181–15187.
14. McGinnis, M.D.; Ostrom, E. Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society*. **2014**, *19*, 2.
15. Burke, M.J. Toward a social-ecological systems perspective for sustainable renewable energy development in Vermont, USA. M.P.A. Thesis, University of Vermont, Burlington, VT, April 2014. Available: http://library.uvm.edu/dissertations/index.php?search_type=item&bid=3094086
16. *Renewable Electricity Futures Study (NREL/TP-6A20-52409);* National Renewable Energy Laboratory: Golden, CO, 2012. http://www.nrel.gov/analysis/re_futures/
17. Soares-Filho, B. S.; Filho, L. C.; Cerqueria, G. C.; Araujo, W. L. Simulating the spatial patterns of change through the use of the Dinamica model. *Simpósio Brasileiro de Sensoriamento Remoto*. **2003**, 721-728. Belo Horizonte: Br. Instituto Nacional de Pesquisas Espaciais.
18. *Farms, land in farms, and livestock operations (2012 Summary, ISBN: 1930-7128)*; U.S. Department of Agriculture: Washington DC, 2013. http://usda01.library.cornell.edu/usda/current/FarmLandIn/FarmLandIn-02-19-2013.pdf
19. *Vermont: 2010. Population and housing unit counts (2010 Census of population and housing, CPH-2-47)*; U.S Census Bureau: Washington DC, 2012.
20. *Vermont Ski Facts;* Ski Vermont, 2014. http://www.skivermont.com/about-us/press-room/vermont-ski-facts (accessed March 17, 2014).
21. Fthenakis, V.; Kim, H. C. Land use and electricity generation: A life-cycle analysis. *Renewable and Sustainable Energy Reviews*. **2011**, *13*, 6-7, 1465–1474. doi:10.1016/j.rser.2008.09.017
22. *Handbook on Siting Renewable Energy Projects While Addressing Environmental Issues*; U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response's Center for

ProgramAnalysis. http://www.epa.gov/oswercpa/docs/handbook_siting_repowering_projects.pdf (accessed October 13, 2013).

23. *Wind energy and wind park siting and zoning best practices and guidance for states*; National Association of Regulatory Utility Commissioners. 2012. http://www.naruc.org/Publications/FINAL%20FINAL%20NRRI_Wind_Siting_Jan12-03.pdf
24. *Siting electric generation in Vermont: Analysis and recommendations (A report to the Governor and the Vermont General Assembly);* Vermont Energy Generation Siting Policy Commission: 2013.http://sitingcommission.vermont.gov/sites/cep/files/Siting_Commission/Publications/FinalReport/Final%20Report%20%20Energy%20Generation%20Siting%20Policy%20Commission%2004-30-13.pdf
25. Blittersdorf, D. *Surviving and thriving in an uncertain energy future.* Presentation conducted at the meeting of the Lake Champlain Regional Chamber of Commerce (Smart about solar), Vermont, April 2010.
26. Ingerson, A. *Cumulative landscape impacts of renewable energy alternatives for northern New England* (Economic analysis). Washington, DC: The Wilderness Society, 2013.
27. *Land-based Wind Energy Guidelines.* U.S. Fish and Wildlife Service. Arlington, VA, 2012.
28. *The three-legged race: Vermont's pursuit of 90% renewables by 2050;* Vermont Energy Partnership, 2013. http://www.vtep.org/documents/07-11-13%20FINAL_CEP_ISSUE_BRIEF.pdf
29. *Renewable Energy Atlas of Vermont*. Vermont Sustainable Jobs Fund, 2014. http://www.vsjf.org/resources/renewable-energy-atlas
30. *Major solar projects list* (fact sheet). Solar Energy Industries Association, 2013. http://www.seia.org/research-resources/major-solar-projects-list
31. *2013 RFP results / 2013 RFP selection (SPEED Program Summary)*. VermontSPEED, 2013. http://vermontspeed.com/ (accessed October 18, 2013).
32. *Public Service Board Orders*. Vermont Public Service Board, 2014. http://psb.vermont.gov/orders (accessed January 24, 2014).
33. Soares-Filho, B. S.; Rodrigues, H. O.; Costa, W. L. Modeling environmental dynamics with Dinamica EGO (Guidebook). **2009** (Rev. Ed., July, 2013, Davis, J. L.). http://csr.ufmg.br/dinamica/dokuwiki/doku.php?id=tutorial:start#guidebook (accessed February 17, 2014).
34. Maeda, E.E.; de Almeida, C.M.; de Carvalho Ximenes, A.; Formaggio, A.R.; Shimabukuro, Y.E.; Pellikka, P. Dynamic modeling of forest conversion: Simulation of past and future scenarios of rural activities expansion in the fringes of the Xingu National Park, Brazilian Amazon. *International Journal of Applied Earth Observation and Geoinformation*, **2011**, *13*, 3, 435–446.
35. Mas, J.-F.; Kolb, M.; Paegelow, M.; Camacho Olmedo, M.T.; Houet, T. Inductive pattern-based land use/cover change models: A comparison of four software packages. *Environmental Modelling & Software* **2014**, *51*, 94–111.
36. Pérez-Vega, A.; Mas, J.-F.; Ligmann-Zielinska, A. Comparing two approaches to land use/cover change modeling and their implications for the assessment of biodiversity loss in a deciduous tropical forest. *Environmental Modelling & Software* **2012**, *29*, 1, 11–23.
37. Schweitzer, C.; Priess, J.A.; Das, S. A generic framework for land-use modelling. *Environmental Modelling & Software* **2011** *26*, 8, 1052–1055.

38. *Vermont Center for Geographic Information* (Web site); Vermont Center for Geographic Information, 2014. http://vcgi.vermont.gov/
39. *BioFinder: Project Development Report*; Vermont Agency of Natural Resources, Montpelier, VT, 2013.
40. *Environmental Impacts of Renewable Energy Technologies*; Union of Concerned Scientists. [Online]. Available: http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-of.html
41. Leung, D.Y.C; Yang, Y. Wind energy development and its environmental impact: A review. *Renewable and Sustainable Energy Reviews* **2012**, *16*, 1, 1031–1039.