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Strategic land use analysis for solar energy development in New York State

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ABSTRACT

This study investigates the spatial characteristics of existing utility-scale solar energy (USSE) development in New York State (NYS) and assesses the land-suitability for the future development of USSE needed to achieve the State's renewable energy goals using GIS-MCDA techniques. Slope, proximity to electric substations, protected lands, and soil quality were used as criteria to develop land suitability scenarios. 40% of present USSE capacity has been developed on agricultural lands, and 84% of identified land suitable for future USSE development (~140 GW potential) is agricultural. The USSE potential on non-agricultural land is 22.5 GW – just sufficient to accommodate the development of 21.6 GW, which is the estimated USSE capacity that will be required to achieve NYS's 2030 goal of 70% renewable electricity. Thus, agricultural lands will be the prime target for future USSE development. Exploring the state-specific synergies for solar-agriculture colocation, preventing the spatially-concentrated development of USSE, and incentivizing the use of unproductive agricultural lands will help mitigate negative impacts of USSE development on agricultural lands.

1. Introduction

Decarbonization of the electricity sector is an essential step towards the reduction of greenhouse gas (GHG) emissions and attainment of the goals set by the Paris Accord [1]. Several national and subnational entities have established ambitious targets for renewable energy generation and decarbonization [2]. Although the United States has yet to set a nationwide renewable energy target, numerous states such as California [3], New York [4], and Massachusetts [5] have codified ambitious clean energy goals. In June 2019, New York State (NYS) enacted the Climate Leadership and Community Protection Act (CLCPA)—setting the most ambitious state-level GHG emissions goal in the country [4]. CLCPA lays out two objectives—generation of 100% of the State's electricity from clean sources by 2040, with an interim target of 70% renewable electricity by 2030, and economy-wide net decarbonization by 2050. In 2018, NYS produced 27% of its electricity from renewable sources, the majority of which is from historically developed hydropower, with only about 5% of total electric production coming from solar and wind [6]. Thus, NYS is expected to experience a massive development of renewable capacity in the upcoming years. According to our estimation, to reach its 70% renewable by 2030 goal, NYS would need additional renewable energy capacity that can produce 54 TWh of electricity annually.

With the decreasing cost of photovoltaic (PV) panels and installed cost, policy incentives for renewable energy, and increasing awareness about the necessity of renewable energy, there has been exponential growth in solar PV capacity in the US [7]. Even in NYS, the capacity of solar PV (both distributed and utility-scale) has grown more than five-fold in the last five years, and this trend is expected to continue [8]. However, as the deployment of USSE reaches new levels, land use conflicts are gaining attention [9]. Solar, with current energy conversion technologies, is a relatively diffuse source for electricity production, and it occupies large swaths of land to collect solar radiation and convert it into electricity [10]. Large USSE installations can occupy hundreds or even thousands of acres of land depending on their capacity [11]. The issue of solar PV land use is even more prominent in NYS, where forests and agricultural land occupy 92% of the State's footprint—land cover types which are not considered particularly suitable for USSE development by the host communities [12,13]. The State is already experiencing growing opposition to USSE development, especially on agricultural lands, as a conflict

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is perceived between the development of USSE and food production [14].

Siting is one of the most crucial decisions in USSE planning, determining not only whether a proposed solar farm will be approved and built, but also the solar installations' economics. Moreover, siting dictates the land use and environmental impacts as well as the public perception and social acceptance of a USSE facility [15,16]. Considering these factors—anticipated massive growth in solar development in NYS, the State's peculiar land cover, and the importance of siting in USSE development—this study aims to investigate the spatial features of USSE development in NYS.

To this end, we developed a spatial model using geographic information systems and multi-criteria decision analysis techniques (GIS-MCDA). Specifically, in this study, we aim to answer three research questions: 1. What are the land-use characteristics of current USSE developments in NYS? 2. How much land in NYS is suitable for USSE installations, and which land cover types do they occupy? 3. How much land might be required for USSE development to achieve the State's interim 70% renewable by 2030 goal? Our ultimate objective for this analysis is to inform solar energy development policies and decision-making from a land-use perspective to support the future development of USSE for transition to sustainable energy. The rest of the article is organized as follows: Section 2 describes the state of the art; the detailed methodology for characterizing existing USSE development, spatial modeling and sensitivity analysis is described in Section 3; Section 4 discusses the results of the feasibility and suitability analysis as well as the policy implications for future solar development; finally, Section 5 provides the conclusion and explores the avenues for future work.

2. Literature review

Owing to the importance of siting and land-use related decision-making for the facilitation of solar PV installation, there is increasing research in the fields of optimal siting and land-use impacts of solar farms. The fundamental objective of such studies is usually similar, which is the identification of the area within a region that is suitable for solar development. However, the actual analysis can take a variety of forms depending upon factors such as the motivation and scope of the analysis, regional specifics, data availability, and current state of solar development in that region. Based on these factors, siting studies may employ a variety of different techniques.

Solar potential can be classified into three categories – geographical, technical, and economic [17]. Such analyses are usually carried out for large regions or for the regions where solar development is at a preliminary stage. Yushchenko et al. conducted GIS-based analysis to determine the geographical and technical generation-potential for solar PV as well as concentrated solar power (CSP) in the underdeveloped region of Western Africa [18]. Similarly, Yang et al. estimated the technical potential for large-scale solar PV for all of China considering the differences in land use factors at various latitudes, slopes, and PV panel technologies [19]. Deshmukh et al. carried out a similar analysis to determine the economic potential for large-scale solar PV and onshore wind in India [20]. GIS-MCDA to assess the geographic potential of solar energy have also been conducted in Afghanistan [21], Tanzania [22], and Bangladesh [23].

Another motivation for land use analysis is to identify specific sites within a region that are optimal for solar development. Such studies are usually carried out in regions where there has already been some solar development, and the geographic scope is small. Doorga et al. analyzed the island of Mauritius to identify the best sites for solar development with consideration to natural factors such as land use, geography, and climate as well as regulations and permitting policies [24]. Ali et al. conducted a similar analysis in Songkhla province in Thailand to identify the optimal locations for the development of solar and wind with due consideration to local conditions that might influence the siting decisions [25]. Giamalaki et al. studied the island of Crete to identify the high priority sites for solar development [26].

Several other motivations for land-use and siting analysis are to investigate the potential impacts of solar development on the environment, changes in land use, or to investigate the impacts of social factors on siting to encourage the solar development in an environment-friendly and socially acceptable way. Such studies are usually performed in regions which have significant current and anticipated capacity of solar installations. Wu et al. investigated the land-use impacts of renewable energy development that is required to achieve California's 100% renewable electricity goals. They assessed how such development can occur with minimal impacts on the environment [27]. Similarly, in a series of studies, Hernandez et al. [15], Moore-O'Leary et al. [28] have tried to identify the land-use and ecosystem impacts of USSE development in California, and Hoffacker et al. [29], Hernandez et al. [30] have assessed the suitability of solar development on low impact lands in the state. Brewer et al. probed into the question of how public opinion affects the development of solar energy in the Southwestern United States. They found that without the consideration of public opinion, suitable land for solar development may be overestimated by as much as 78% [31]. Drechsler et al. investigated the spatial pathways that allow an efficient as well as socially equitable allocation of solar and wind power plants in Germany [32].

Application of GIS-MCDA for siting usually follows a general algorithm, as depicted in Fig. 1. Criteria used in any siting and land-use analysis are informed by the scope of analysis and data availability. Determining appropriate criteria is an important step in siting analysis as the relevance of the same criteria can be much different in different situations. For example, risk of wildfires and water availability are important criteria that are used in siting analysis for Arizona [13]; however, they do not hold the same relevance in NYS. Usually, both primary and secondary data collection methods are used in determining criteria significance. Primary data collection, which includes experts' input and/or public opinion surveys, helps identify the region-specific relevant criteria. Criteria used in GIS-MCDA analysis are typically categorized into four types – technical, economic, environmental, and social [33]. For GIS-MCDA implementation, criteria are categorized as constraints/exclusion or preferences/suitability. Exclusion criteria are binary values used to identify surfaces where solar development can/cannot take place. Some of the most common exclusion criteria include legal restrictions, protected lands, developed areas, open water, and higher slope surfaces [34]. Suitability criteria are used to identify which area in the feasible region might be the best for solar development. Some of the most common suitability criteria include solar irradiation, distance to electric infrastructure, slope, and land cover [34].

A feasibility surface is created by combining all the exclusion criteria in GIS. It is the process of determination of relative importance of suitability criteria, where the MCDA algorithms are used. Different methodologies from MCDA are used to determine the relative importance of various decision criteria. Al Garni et al. used analytical hierarchy process (AHP) to determine the weights of suitability criteria to generate a suitability surface for Saudi Arabia [35]. AHP has been used in several more solar site suitability analyses, such as Limassol district in Cyprus [36], Southeastern Spain [37], Eastern Morocco [38], England [39]. GIS-AHP constitutes the most widely used MCDA algorithm for solar siting analysis [13],

Fig. 1. Typical procedure for the implementation of GIS-MCDA technique.

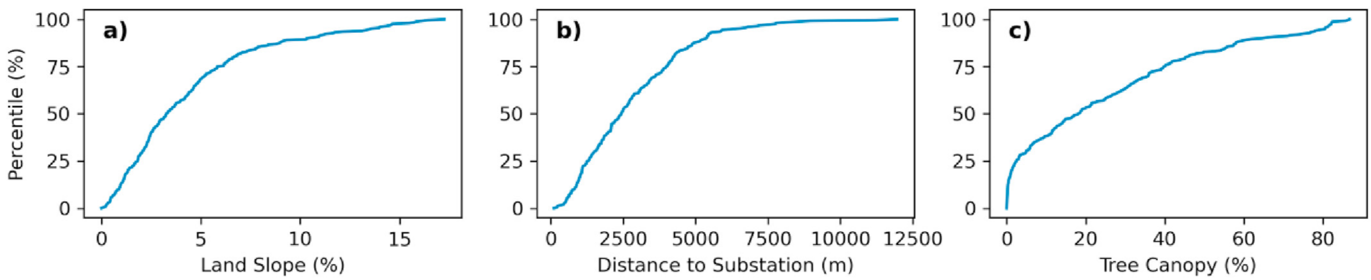

Fig. 2. Land use analysis of existing USSE installations in New York State – (a) In terms of slope of the land (b) in terms of distance from electric substations, and (c) in terms of percent tree canopy.

and sustainable energy planning [40]. Another MCDA algorithm widely used in siting analysis is ELimination and Choice Expressing Reality (ELECTRE) [41,42]. MCDA methods require some form of subjective input from the decision-makers or domain experts. After determining the relative importance of preferences using one of the MCDA methodologies, one can generate a suitability surface that divides the feasible area into different tiers.

3. Method

Following the method accepted within the literature, we have employed the GIS-MCDA methodology for this analysis. All the spatial analysis was performed in the ArcGIS Pro software (version 2.3) [43].

The methodology for this study follows a seven-step process: 1. Identification of criteria affecting solar development and data collection, 2. Analysis of criteria based on existing solar PV installations, 3. Creation of a feasibility surface, 4. Creation and analysis of various suitability scenarios, 5. Sensitivity analysis to assess the robustness of the suitability model, 6. Estimating land use requirements for the state's energy goals, 7. Investigation of suitable land availability and land requirement at the county and state level. Stage 1–5 are primarily tied to the first research question, i.e., how much land is available in the NYS for USSE development. Stage 6 is tied to the second research question, i.e., how much land might be required to satisfy NYS's energy goals. Stage 7 combines these two analyses to answer the third research question – where the prospective solar development would take place.

3.1. Identification of criteria

We utilized expert interviews, permitting policies in NYS, and a literature review to inform our choice of criteria. We identified slope, land cover, distance to the electric infrastructure, quality of farmland, and protected areas as essential considerations for USSE siting in NYS. Table 1 lists all the criteria used in this study and their data sources.

3.2. Analysis of criteria using existing solar PV installations

3.2.1. Preparation of existing solar installations data

We created a comprehensive list of 336 solar installations in NYS with capacity above 1 MW and which are either completed or under-development. The 1 MW threshold was chosen based on the EIA definition of utility-scale power plants [6]. The list of solar installations was compiled from the New York State Energy Research and Development Authority (NYSERDA) Large Scale Renewable Database, the NY-SUN Projects Database, and the EIA database of utility-scale power plants. Each power plant is represented as a point described by its spatial coordinates. To account for the power plant's land footprint, a square whose area equals the capacity-based land footprint of the individual solar PV installation was created.

3.2.2. Criteria analyses

The spatial criteria of slope, land cover, farmland quality, and distance from electric substations were analyzed against the existing solar installations. ArcGIS functions Spatial Statistics (for continuous data such as slope and distance) and Tabulate Area (for discrete data such as land cover and farmland class) were used for this analysis.

3.3. Creation of a feasibility surface

For the feasibility surface and all the spatial analysis henceforth, a 30m by 30m horizontal grid (900 m^2 pixel size) across the entire area of NYS was used. The feasibility surface, thus, is a binary surface with each pixel characterized as either feasible or infeasible. Table 2 depicts feasibility conditions.

Using the Raster Calculator function, each pixel meeting any of these infeasibility conditions was classified as infeasible. All the remaining pixels were classified as feasible for solar development.

3.4. Creation and analysis of suitability scenarios

3.4.1. Criteria evaluation

We created suitability scenarios to further examine the

Table 1
Criteria used for siting analysis in this study and their corresponding data sources.

Criteria	Data Source and Description
Spatial extent – NY State, Counties, City/Towns, villages – civil boundaries	NY State GIS Clearinghouse – a geodatabase containing polygons for each entity
Slope and Aspect	National Elevation Dataset 1 arcsec Digital Elevation Model (NED - DEM) [44]
Land Cover	National Land Cover Dataset (NLCD) for NYS [12] NLCD – Tree Canopy Cover data for NYS [45]
Electric Substations	1. Department of Homeland Security - Homeland Infrastructure Foundation-Level Data (HIFLD) – Electric Substations [46] 2. Transmission AtlasTM; 2013 (Electric substations with <115 kV capacity) [47]
Quality of Farmland	NRCS Farmland Class from SSURGO soil survey database [48]
Protected Areas	1. PADUS - A comprehensive database of the protected areas in the US [49] 2. Wetlands - National Wetlands Inventory (NWI) from the US Fish and Wildlife Service [50] 3. NYS Department of Environmental Conservation - Environmentally Critical Areas 4. NYS Office of Parks, Recreation and Historic Places 5. National Register of Historic Places

Table 2
Criteria used to determine the feasibility of land for USSE development along with their infeasibility conditions and reasons for infeasibility.

Feasibility Criteria	Infeasibility condition and description	Reason for infeasibility
Protected Areas	Adirondack Park NYDEC Critical Environmental Areas Wetlands with area >12.4 acres including a 100 ft surrounding buffer zone	Areas with a legal restriction against development by NYSDEC [51]
	PAD US Database sites with GAP status 1 and 2 (GAP status for an area indicates the intent of managing that area from the biodiversity perspective)	Areas with very high biodiversity and thus possible legal restrictions against development at the state and/or federal level [27]
	National Register of Historic Places NYSOPRHP Parks, Recreation and Historic Places	Areas with very high aesthetic and social value with possible legal restrictions against development [13,27]
Slope (%)	>13.5%	95th percentile of mean slope for existing solar installations (Refer to Fig. 2a)
Land Cover (NLCD)	NLCD Land cover classes - Unclassified; Open Water; Perennial Ice or Snow; Developed, High Intensity; Developed, Medium Intensity; Developed, Low Intensity; Developed, Open Space	The physical impossibility of building solar on these land cover types or outside of the NYS

feasibility surface. For examining land suitability, the slope, land cover, distance to electric substations, and farmland quality were studied. Each criterion was classified as good (score 3), medium (score 2), poor (score 1), or least suitable (score 0), as summarized in Table 3.

A literature review (see Table 4), as well as the analysis of existing solar installations, were used to determine criteria classification. A detailed description of each criterion is provided in the following subsections.

Some criteria – namely slope, distance to substation, and percent tree canopy – vary substantially among existing solar installations, so historical trends in these criteria can aid in determining site suitability. Fig. 2 depicts the ranges for these three criteria for USSE installations in New York State, and each criterion is discussed in detail in the following sections.

3.4.1.1. Slope. The slope of the land is an important characteristic that affects both the construction cost of the solar farm as well as its electricity production [35]. No consensus exists surrounding what values of slope are more suitable [19]; hence for this analysis, we used data gathered from existing solar installations to determine the scoring – the 50th percentile, the 80th percentile, and the 95th percentile slope values were 3%, 7%, and 13.5%, respectively. These values are in good agreement with the values reported in the literature (Table 4). Thus, the range of 0–3% slope was deemed good; the range of 3–7% slope was deemed medium, and the range of 7–13.5% slope was deemed poor (Refer to Fig. 2a for slope percentile graph).

3.4.1.2. Land cover. For determining the suitability of land cover types, both the criteria used in previous siting analysis (Table 4) as well as the definition of land cover types from NLCD were used.

Table 3
Scoring of suitability criteria.

Criteria	Criteria Unit	Good (3)	Medium (2)	Poor(1)	Least Suitable(0)
Slope	%	0–3	3–7	7–13.5	>13.5
Land Cover	NLCD land cover type	Barren Land; Herbaceous; Hay/Pasture; Cultivated Crops	Deciduous Forest; Evergreen Forest; Mixed Forest Shrub/Scrub; Woody Wetlands; Emergent Herbaceous Wetlands		All the infeasible land classes used for feasibility surface
Quality of Farmland	NRCS farmland class	Not Prime Farmland (15), NODATA	Prime Farmland, if drained (16); Prime Farmland, if protected from flooding (23)	–	Prime Farmland (1), Farmland of Statewide Importance (3), Farmland of Unique Importance (14)
Distance from Electric Infrastructure	Distance to substations (m)	0–2500	2500–4000	4000–6500	>6500

Table 4
Criteria classification used in literature.

Study and Study area	Slope	Grid Distance	Land use restrictions
BLM/DOE Final Programmatic Environmental Impact Statement A.2.6 [52] **Southwestern United States**	<5% (<2% preferred)	Closer the better	–
Best Practices for Siting Solar Photovoltaics on Municipal Solid Waste Landfills [53] **United States**	<5–10%	0-3 miles (<0.5 miles preferred)	–
PVMapper -DoE Solar Site Analysis Tool [54] **United States**	<5%	<24 miles (<12 miles preferred, >235 kV)	–
Yang et al. [19] **China**	<3%, 3–20%, 20%	–	Legal restrictions, farmland, dense surface vegetation, water bodies, and built-up areas
Majumdar, and Pasqualetti [13] **Arizona, US**	<3%, 3–5% & 5–8.75% (south aspect), 5–8.75% (other aspects)	<1 mile, 1–3 miles, 3–6 miles	Developed areas, crop, pasture, military land, forests, parks etc.
Sward et al. [55] **New York, US**	<5%	<1 mile	size, prop class, forests
Palmer at al [33]. **United Kingdom**	<18% (<5% is preferred)	<2.5 km, < 10 km, constraints on grid capacity	national parks, urban location, mountains, flood zone, forests, prime agricultural land
Yushchenko et al. [18] **Western Africa**	<10%	1–5 km, 5–30 km, 30+km	Surface occupied by built-up areas (other than urban), agricultural zones, forests, wetlands, and water bodies
Al Garni and Awasthi [35] **Saudi Arabia**	<5%	<50 km, closer the better	urban areas, protected land, major road networks
Hernandez et al. [30] **California, US**	<5%	<10 km	–
Wu et al. [27] **California, US**	<3%	Closer the better	Parks, forests, farmland

Land cover types that are already modified by human activities to some extent were deemed good (barren land, pastureland, cropland, and herbaceous area—like grassland). Land cover types where solar farm development might prove to be more expensive and will have a moderate impact on the environment were deemed medium (all forests, wetlands, and shrub or scrubland). Land cover types where it is infeasible to develop utility scale solar were deemed least suitable.

3.4.1.3. Quality of farmland. Although farmland is most suitable for solar development in terms of land characteristics (flat, already cleared of natural vegetation, and close to some form of electric infrastructure), there are rising concerns about the use of farmlands for solar development and the conflict between energy production and food production [14]. To assess the suitability of farmland, the National Soil Survey Handbook created by Natural Resources Conservation Service (NRCS) describing each farmland class was used [56]. According to NRCS, 'prime farmland' is the land that has the most appropriate combination of chemical and physical features for the production of most (edible/inedible) crops. 'Farmland of statewide importance' is the land that nearly meets the criteria for prime farmland. Farmland type designations do not depend upon the current use of the land [56]**.** The areas that are not prime farmland or where no data exist about the quality of soils were deemed good; the farmlands that could have been prime if drained or protected from flooding were considered medium, and the prime farmlands, along with the farmland of statewide importance, were deemed least suitable.

3.4.1.4. Distance from electric substations. Like land slope, the distance from electric infrastructure is an essential criterion for siting solar farms; however, there is no agreement around a specific cutoff distance defining suitable or unsuitable as is evident from Table 4. Again, we resorted to analysis of existing solar installations. The 50th percentile, the 80th percentile, and 95th percentile distance values were 2500 m (~1.5 miles), 4000 m (2.5 miles), and 6500 m (~4 miles), respectively; thus, we deemed the range of 0–2500 m good, 2500–4000 m medium, 4000–6500 m poor, and greater than 6500 m least suitable. It must be noted that this analysis assumes that all the electric substations have the capacity for additional interconnections, i.e., they are electrically unconstrained—which may or may not be the case. Although this factor is important, we cannot consider it due to a lack of data. (Refer to Fig. 2b for percentile graph for distance from electric substations criterion).

3.4.2. Model creation and analysis

3.4.2.1. Generation of suitability map. The criteria were applied using the Raster Calculator function in ArcGIS Pro on the same spatial grid of 30m by 30m that was used for the creation of the feasibility surface. Each pixel belonging to the feasible area was assigned a score equal to the equal-weighted sum of its scores in each of the four criteria. The pixels in the infeasible area retained their original score of 0; thus, each pixel got a score between 0 and 12. The score was further reclassified into a four-level suitability classification using the mapping in Table 5.

3.4.2.2. Suitability surface analysis and refinement. We created four suitability scenarios to analyze the effects of restrictions on an individual criterion or group of criteria. Beginning with the base case, each scenario becomes increasingly restrictive.

1. Base Case Scenario:

A feasible region pixel would be deemed unsuitable only if it scored zero in all the criteria. This is the least restrictive scenario.

2. No Expansion of Electric Infrastructure Scenario:

A feasible region pixel would be deemed unsuitable if it scored zero under the criteria of 'distance from electric substations' irrespective of its scores under all other criteria.

3. Opposition to Development on Prime Farmland Scenario:

A feasible region pixel would be deemed unsuitable if it scored

Table 5
Mapping technique used for reclassifying pixel score to suitability.

Original score of each pixel	Reclassified score	Justification	Suitability
10–12	3	Scored 'good' in at least three criteria	Good suitability
8–9	2	Scored 'medium' or above in at least three criteria	Medium suitability
1–7	1	Rest of the area from feasible region	Poor suitability
0	0	Infeasible or scored 'least suitable' score in each criterion	Not suitable

zero under the criteria of 'quality of farmland' irrespective of its scores under all other criteria.

4. Opposition to Farmland Development and No Expansion of Electric Infrastructure:

A feasible region pixel would be deemed unsuitable if it scored zero under the criteria of 'quality of farmland' OR if it scored zero under the criteria of 'distance from electric substations' irrespective of its scores in all other criteria. This scenario is the most restrictive.

The most restrictive scenario of 'Opposition to Farmland Development and No Expansion of Electric Infrastructure' was then further refined using a percent tree canopy condition followed by the contiguity condition. The NLCD defines a forest land cover pixel (deciduous, mixed, and evergreen) as a pixel with at least 20% coverage by the respective types of trees. Thus, a pixel classified as one of the forest land covers can be anything ranging from a small grove of trees to a thick forest—a condition that can drastically alter the suitability of that forest pixel for USSE development. To account for this difference, we used the NLCD tree canopy data to differentiate the forest pixels that are suitable for solar development from the ones that are not. Due to the lack of literature using tree canopy in suitability analysis, the threshold for the percent tree-canopy criterion was determined from the analysis of existing solar installations. We found that 80% percent of all the existing solar installations utilize area with a mean tree canopy of 45% (Refer to Fig. 2c for percentile graph for percent tree canopy); thus, forest pixels with higher than 45% tree canopy were deemed unsuitable for solar development.

Then, the contiguous area condition was applied on the resultant surface. The suitability surface for the Opposition to Farmland Development and No Expansion of Electric Infrastructure' scenario was assessed for contiguous areas in each suitability tier. All the contiguous parcels from the medium/good suitability areas whose size is less than 26,000 m^2 (approximately equal to the land footprint of 1 MW of solar calculated using the NREL estimate of 39 MW km^{-2} [11]) were reclassified as unsuitable. A detailed description of the GIS procedure for this analysis can be found in supplementary information – Section S1.

3.5. Model sensitivity analysis

In addition to the scenarios studied in Section 3.4, a sensitivity analysis was completed to determine the impact of input land criteria weights on the model output. In the primary study, equal weights were assigned to all input land criteria. For example, distance to electrical infrastructure and slope each contributed equally to the pixel's final overall score. While this provided a useful base case, the effect that each individual criterion had on the model's output was also explored through a sensitivity analysis to confirm the validity of this equal-weighting assumption. The sensitivity analysis was conducted by assigning weights to each of the input criteria, varying those weights by a Monte Carlo simulation approach, and exploring the results. A full description of the sensitivity analysis method can be found in Supplementary Information Section S2.

3.6. Determination of land use requirements towards New York State's energy goals

In this stage of analysis, we attempted to assess the land requirement for solar development given NYS's goal of generating at least 70% of its electricity from renewable resources by 2030 (70 by '30) [4]. The data for NYS's 2018 capacity and electricity generation was garnered from EIA's monthly reports [57], and 2030 electricity forecasts were obtained from the New York ISO Gold Book 2019 [58]. To calculate the USSE capacity required to fulfill the goals of NYS, the following equation was used (Refer the supplementary information Section S4 for elaboration.)

$$C_{USSE} = \frac{0.7 \times (D_{2030} - RE_{2018} - RE_{ADD})}{8760 \times CF_{USSE}}$$

where C_{USSE} is the required capacity of USSE in New York in 2030, D_{2030} is the 2030 forcast electrial demand, RE_{2018} is the amount of electricity that was generated by renewable energy in 2018, RE_{ADD} is the expected amount of electricity that will be generated by renewable energy resources added between 2018 and 2030, and CF_{USSE} is the capacity factor of USSE in New York.

For additional renewable electricity generation, it was assumed that the capacity of onshore wind and hydro would remain constant at its 2019 level, and the State will have realized its goals of 6 GW of distributed solar and 9 GW of offshore wind with no additional development. The corresponding land requirement was calculated using NREL's land-use factors for USSE installations [11].

3.7. Investigation of suitable land availability and land requirement

We estimated the distribution of suitable area across the different land covers, the potential for USSE development on agricultural and non-agricultural land, and we compared it to the USSE capacity that could be necessary to fulfill the state's 70 by '30 goal. We also wanted to assess the county-wise suitability of USSE development. One of the ideal methods for this analysis would have been a statistical model to determine which characteristics of a county (e.g., percent living in poverty, average level of education, average income, etc.) influence solar siting decisions [59,60]. However, this approach would be challenging to implement in the current analysis due to a lack of sufficient data points, i.e., existing USSE installations, to formulate and run such a model. Another shortcoming of this approach is that USSE development in NYS is in the early stage, and the decision criteria for such early-stage development might differ from that used for later-stage development. Hence, the county-wise suitability assessment was not carried out.

4. Results and discussion

This section is divided into five parts. First, we discuss the results of the analysis of existing solar installations in NYS in terms of their land use. Then, we present the findings for the feasibility surface and the suitability scenarios followed by a brief discussion of results of the sensitivity analysis. Next, the results of the future

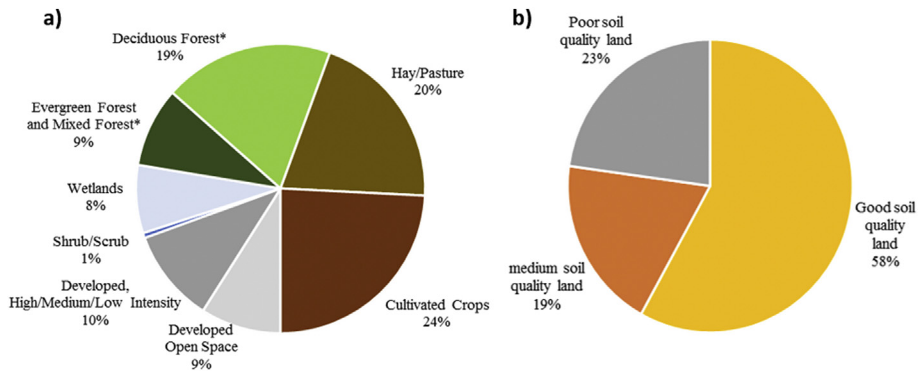

Fig. 3. Land use analysis of existing USSE installations in New York State – (a) In terms of land cover (using National Land Cover Dataset) (b) In terms of quality soil (using National Soil Survey Dataset).

solar development estimate and the land cover suitability analyses are presented and discussed. At last, the policy implications of this analysis are discussed.

4.1. Analysis of land use of existing solar development

Fig. 3 depicts the land use of the existing USSE installations in NYS. Fig. 3a depicts the land use of existing USSE installations in terms of the land cover. This graph employs the same land cover categories that are employed by the NLCD.

The most abundant types of land cover occupied by these installations are hay/pasture and cultivated crops. These land types together account for a little less than half (44%) of all the land occupied by USSE installations. Another significant chunk of USSE installations have occurred within forests. Evergreen, mixed, and deciduous forests, taken together, represent approximately 28% of all the land area that is occupied by the solar farms in the state.[1] These observations are consistent with the fact that forests and agricultural land represent the most abundant and the second most abundant land covers in the NYS. Moreover, these results also validate the sentiment that has been echoed among experts that the majority of solar development in the state has occurred on agricultural land [14]. Probable reasons for this phenomenon could be that agricultural lands generally have a low slope, are cleared of trees and other natural vegetation, and contain large, contiguous parcels of land. Due to the requirement of electricity supply to operate farm equipment, agricultural lands usually also offer close proximity to electric infrastructure [61].

Fig. 3b depicts the land use of existing USSE installations in terms of the quality of soil, which is represented by the farmland class. Good soil quality corresponds to the 'Prime Farmland' and 'Farmland of Statewide Importance' categories defined in the National Soil Survey data [56]. Medium soil quality corresponds to the 'Prime Farmland, if Drained' category, and poor soil quality corresponds to the 'Not Prime Farmland' category from the National Soil Survey data. It must be noted that the National Soil Survey takes into consideration only the quality of surface soil and does not consider the actual use of the land, unlike the National Land Cover data. In terms of actual use (land cover), prime farmland, represented in the pie chart Fig. 3a by the term good soil-quality land, can be a forest, hay/pasture, shrub/scrub, or cultivated cropland. From the land use analysis, it can be inferred that agricultural land and land with good soil quality is, indeed, the preferred land for USSE development so far. This trend, if continued unabated, could give rise to the continued conversion of productive agricultural land into land covered by USSE installations—a trend that could negatively impact the agro-economy in the state.

4.2. Feasibility surface and suitability scenarios

4.2.1. Feasibility surface characterization

To create the feasibility surface, two types of criteria were used – land where legal restrictions against development exist and land where solar development is not possible due to its physical characteristics. The first set of criteria included data such as wetlands, PADUS, critical environmental areas, whereas, the slope and land cover constituted the second set of criteria. Table 6 presents the result of the feasible land analysis considering both the sets of criteria and, finally, their combination. Fig. 4 depicts the final feasibility map for NYS. Even after considering both the sets of stringent criteria, around 46% of NYS land is feasible for solar development, representing a technical potential of 2235 GW.

4.2.2. Assessment of suitability scenarios

Suitability scenarios were created to investigate the impact of 'least-suitability' in one or more criteria on the overall suitability of land for USSE development in NYS. The results are presented in Table 7 and Fig. 5. The land with good suitability remains almost constant even with increasing restrictions for the criteria of electric substations and prime farmland. In the case of the medium suitability land, there is a reduction of 11% from Scenario 1 to Scenario 2, and a reduction of 41% from Scenario 1 to Scenario 3. It can be inferred that around 89% of medium suitability land from the base case does not belong to the least-suitable category from the perspective of distance from the electric substations criterion. This means that 89% of the land in medium suitability is within 6500 m (~4 miles) of electric infrastructure representing a technical potential of 605 GW; thus, it can be inferred that the lack of electric infrastructure, if well distributed, will not prove to be a bottleneck for solar development in the State.

There is a substantial decrease (41%) in medium suitability land from scenario 1 to scenario 3. Even with such a significant decrease, there is a technical potential of 403 GW of USSE development on medium suitability land. Both scenarios (Scenario 2 and Scenario 3) were combined to create Scenario 4. As can be seen from Table 7, the technical potential for USSE on lands which are not prime

[1] However, this 28% forest land should be interpreted with caution; in NLCD, the criterion for a pixel to be categorized into any of the forest land cover types is, if 20% or more area of a pixel is trees, then that pixel is categorized as a forest pixel. Hence, a forest pixel can represent dense vegetation, or it could very well be an isolated bunch of trees. Our analysis, discussed in subsequent section, has found that for existing USSE installations, the 80th percentile for the percent tree cover criterion is 45%.

Table 6
Area that is feasible for solar development in NYS considering restrictions individually posed by protected areas, physical conditions of the land, and their integration.

Feasibility criteria used	Feasible Area in sq. miles (% of NYS total area)	Infeasible Area in sq. miles (% of NYS total area)
Physical conditions – land cover and slope	31,519 (64%)	17,421 (36%)
Protected areas – PADUS, wetlands, state parks, places of recreational and historical importance, environmentally critical areas	33,321 (68%)	15,672 (32%)
Combination of both sets of criteria	22,382 (46%)	26,550 (54%)

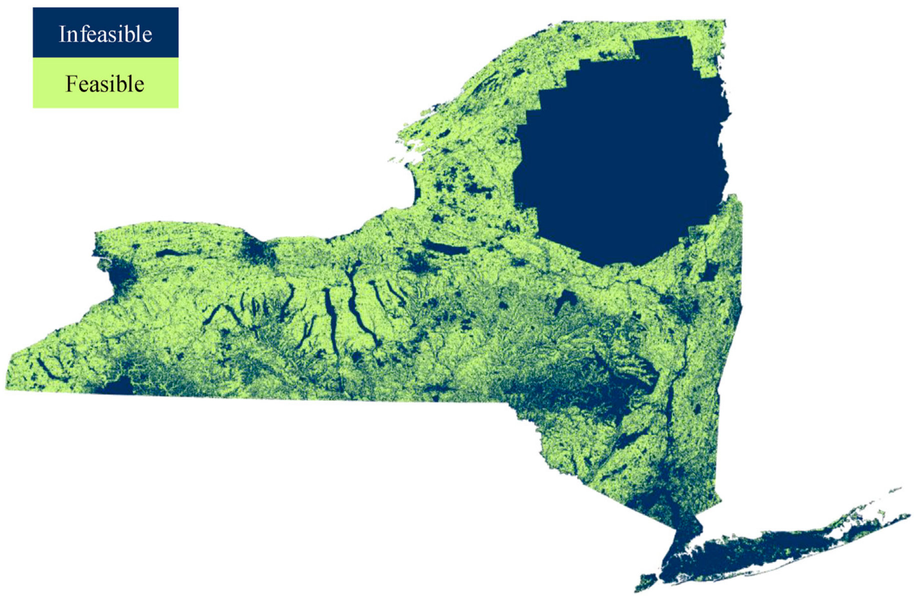

Fig. 4. Feasibility map of New York State.

Table 7
Impact of suitability of individual criteria on overall land availability and corresponding potential USSE capacity in NYS.

Scenario		Unsuitable	Poor Suitability	Medium Suitability	Good Suitability
1. Base Case	Land availability (sq. miles)	26,538	13,045	6816	2515
	Technical potential (MW)	0	1302,450	680,496	251,093
2. No Expansion of Electric Infrastructure	Land availability (sq. miles)	31,809	8523	6068	2515
	Technical potential (MW)	0	850,891	605,819	251,093
3. Opposition to Development on Prime Farmland Scenario	Land availability (sq. miles)	37,413	2218	4045	2486
	Technical potential (MW)	0	221,444	403,810	248,216
4. Opposition to Development on Prime Farmland and No Expansion of Electric Infrastructure	Land availability (sq. miles)	39,520	794	3358	2486
	Technical potential (MW)	0	79,300	335,255	248,216

farmland and are within 6500 m distance from an electric substation is approximately 335 GW in medium suitability land and 248 GW in good suitability land.

4.2.3. Investigation of good and medium suitability land in the most restrictive scenario (scenario 4)

Not all technical potential can be economically harnessed. Hence, we decided to refine the most restrictive scenario of 'Opposition to Development on Prime Farmland and No Expansion of Electric Infrastructure' using tree canopy and contiguity criteria, as described in Section 3.4.2.2. After implementation of the tree canopy criterion (Scenario 4.1), a 63% reduction in medium suitability land and a 39% reduction in good suitability land was observed compared to the original scenario. Subsequently, the technical potential was reduced from 335 GW to 115 GW on medium suitability land and from 248 GW to 150 GW on good suitability land. After applying the contiguity condition (Scenario 4.2), the technical potential was further reduced to 56 GW and 90 GW on medium and good suitability lands, respectively; thus, without the implementation of the tree canopy and contiguity criteria, the

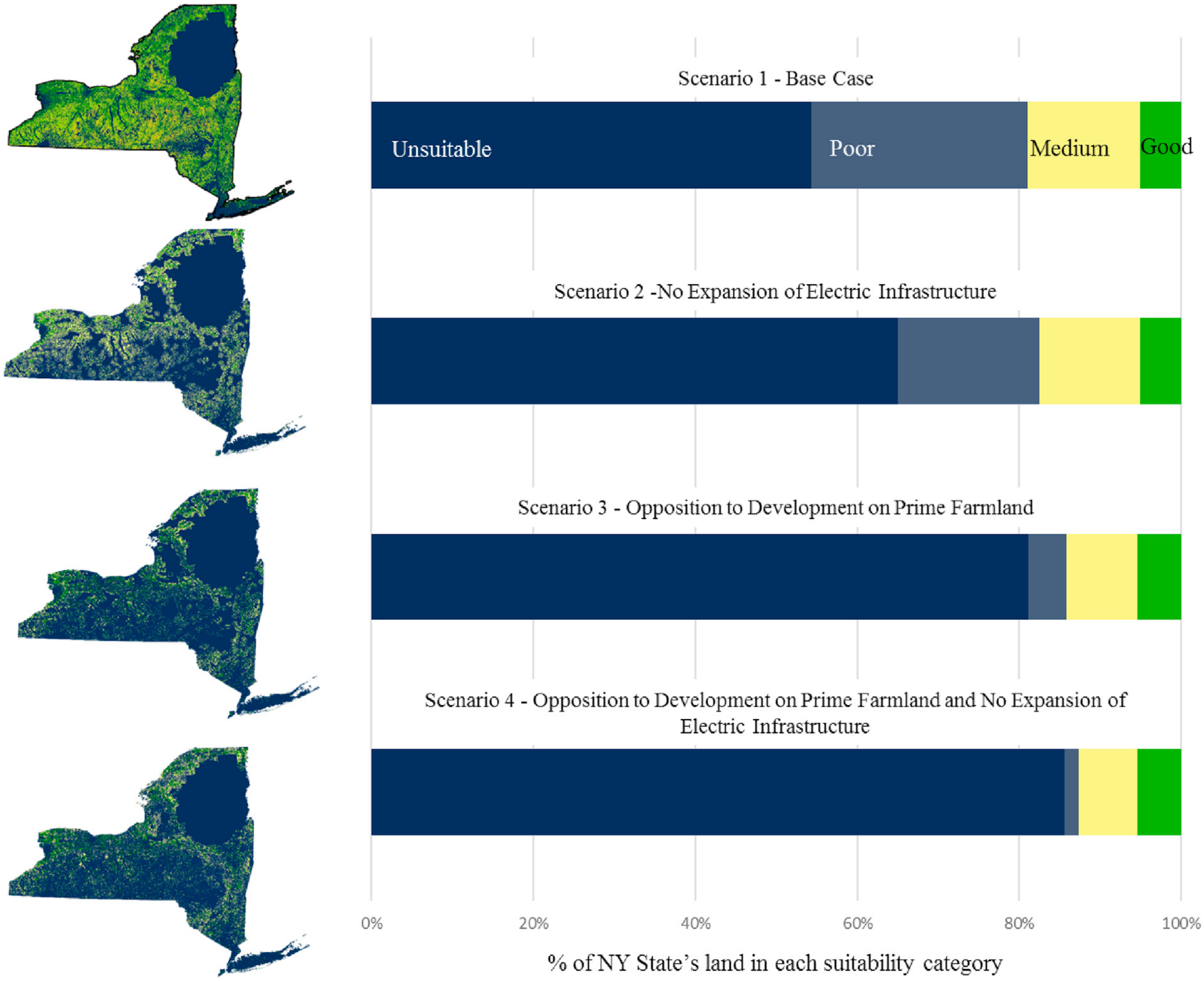

Fig. 5. Assessment of land availability for USSE development across various suitability scenarios.

technical potential for USSE is overestimated by as much as 83% on medium suitability land and 64% on good suitability land as depicted in Fig. 6.

The good and medium suitability land in Scenario 4 was analyzed against NLCD, both before and after the tree canopy and contiguity implementation, to observe the changes in distribution of suitable land and corresponding development potentials across different land covers (Fig. 7).

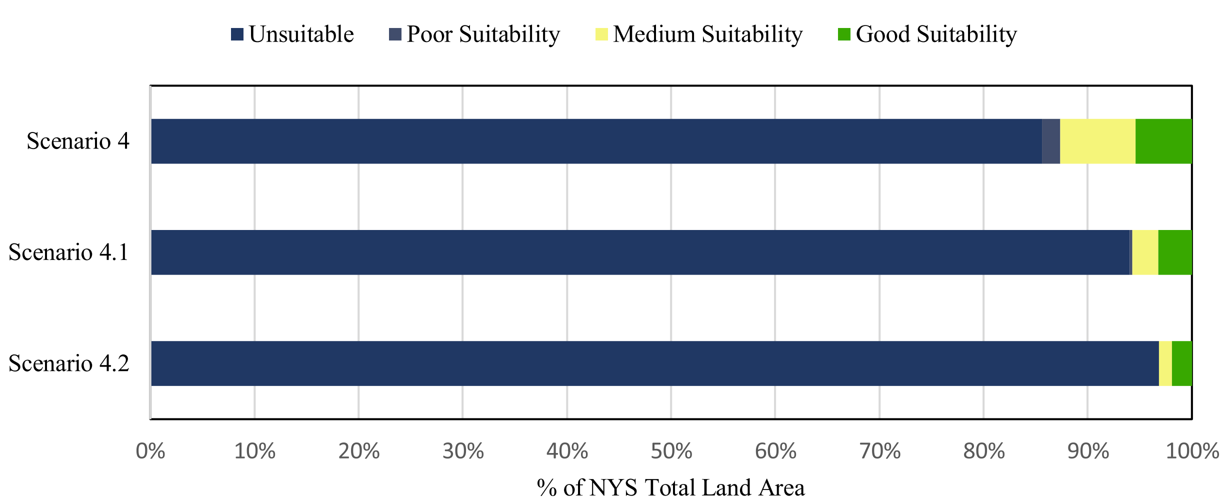

Fig. 6. Suitability analysis of Scenario 4 - 'Opposition to Development on Prime Farmland and No Expansion of Electric Infrastructure' post-implementation of the tree canopy and contiguity criteria.

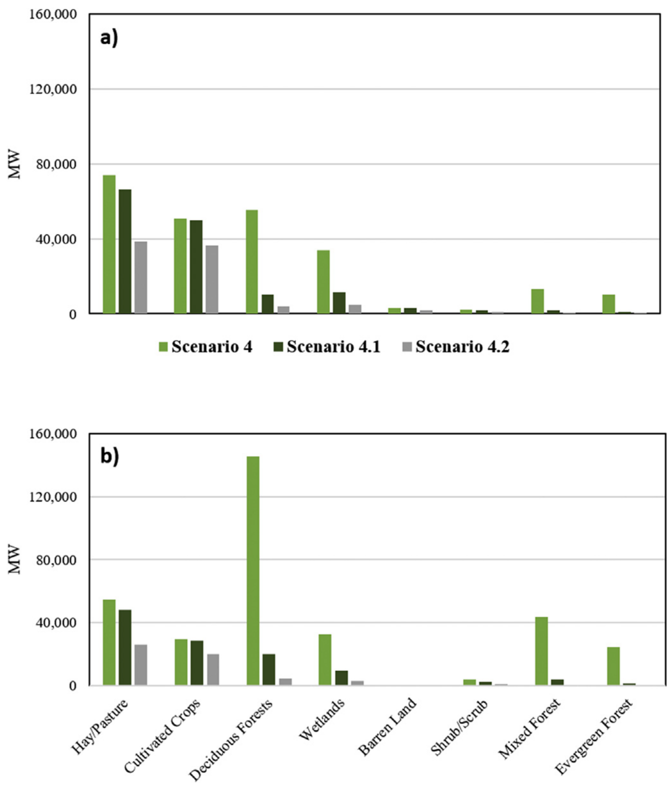

Fig. 7. Technical potential of USSE development in (a) good and (b) medium suitability land across different land covers for the original scenario and after implementation of the tree canopy and contiguity criteria.

There is a precipitous drop in the USSE potential of good- and medium-suitability land in all three forest land cover types signifying the importance of the tree canopy criteria. Interestingly, it can be observed that cultivated crops and hay/pasture are still the most common land cover types for both good- and medium-suitability land.

4.3. Sensitivity analysis

As noted in Section 3.5, a Monte-Carlo sensitivity analysis was conducted to assess whether the base assumption of equal weightings (for each input criteria: slope, soil quality, distance to electrical infrastructure, and land cover) in determining the final score of a pixel was reasonable. A full description of the sensitivity analysis results can be found in the Supplementary Information Section S3. We found that model outputs associated with medium and good suitability land for solar development are relatively insensitive to model inputs as seen in Fig. 8. In each panel of Fig. 8, a set of four dots that align vertically represents a model run, where the weight attributed to the input parameter is plotted on the x-axis and the percent of the total area of the that model run that received a certain overall score (indicated by color) is plotted on the y-axis. On average, introducing random variation in the weightings of the input paramaters by a standard deviation of 0.106 only increased the standard deviation of pixels' overall scores within output maps by 0.083 and increased the mean by 0.032. On aggregate, both are small changes in the output maps, where a whole point (1.000) determines a change in the classification of a cell from one level of suitability to another. Therefore, the results from the overall output map do not change significantly due to different weightings of importance of the input parameters.

As such, our initial assumption that each of the input criteria have equal importance in determining the output map provides a reasonable estimate for the amount of land that is for suitable solar development, even if the actual weight or importance of the input criteria are in reality, not equivalent. Further, these results suggest that if the importance or weight of one of the input criteria changes, perhaps due to certain policy actions, the total amount of land suitable for solar development remains roughly the same. However, if there is a significant shift in government policy or social attitude, the classification systems for the input data should be examined and an additional sensitivity analysis should be conducted.

Finally, we believe that the Monte-Carlo sensitivity analysis method could be implemented on any GIS siting model and could be used to determine if a chosen initial weighting estimation of the input criteria provides a reasonably stable output solution. Further, input criteria that have a large effect on the results could be identified alerting developers, operators, and policy makers of factors that could affect the locations of future renewable energy technologies.

4.4. Land requirement for future USSE development and its comparison with the availability of suitable land

Using the methodology detailed in Section 3.6, NYS is forecasted to require approximately 21.6 GW of USSE capacity by 2030 to fulfill its 70 by '30 goal. Fig. 9 depicts the technical potential for USSE on good-suitability and medium-suitability land in Scenario 4 with tree canopy and contiguity criteria implemented. Total USSE potential available in this case is 140 GW (85 GW on good-suitability land and 55 GW on medium-suitability land), which is still 6.5 times greater than the estimated requirement of 21.6 GW.

However, on good-suitability land, all the land types other than hay/pasture and cultivated crops, together, have only a 12.5 GW capacity potential. Similarly, on medium-suitability land, all the land types other than hay/pasture and cultivated crops, together, have approximately a 10 GW capacity potential. Collectively, this 22.5 GW capacity potential is barely enough to satisfy our forecasted requirement of 21.6 GW. If USSE development is to be pursued only on good-suitability lands, then, according to the current model and USSE capacity forecast, at least 10 GW of USSE development needs to take place on the hay/pasture and cultivated crops land cover types.

4.5. Policy implications for USSE development in NYS

4.5.1. Prevention of spatial concentration of USSE development

Since 2014, USSE capacity in NYS has grown at an annually compounded rate of approximately 46.5% [6]. This analysis has found that around 41% of existing USSE installations are located on agricultural land. Furthermore, 85% of the good-suitability land for USSE development is agricultural land, and so is 82% of the medium-suitability land.

Given the land-use trend so far and the characteristics of identified good- and medium-suitability lands, agricultural land will likely remain the prime target for future USSE development. Preventing the local concentration of solar farms could help to mitigate the negative impacts of USSE development on local agriculture and economic activities dependent on it. During one of the interviews that was conducted for this analysis, an expert conveyed that concentration of USSE installations on agricultural land that leads to the conversion of a considerable amount agricultural land into solar farms initiates a chain reaction through all the businesses that depend upon the operation of farms.

To avoid such concentration of USSE installations, pre-existing USSE capacity in a given locality (city/town/county) could be used

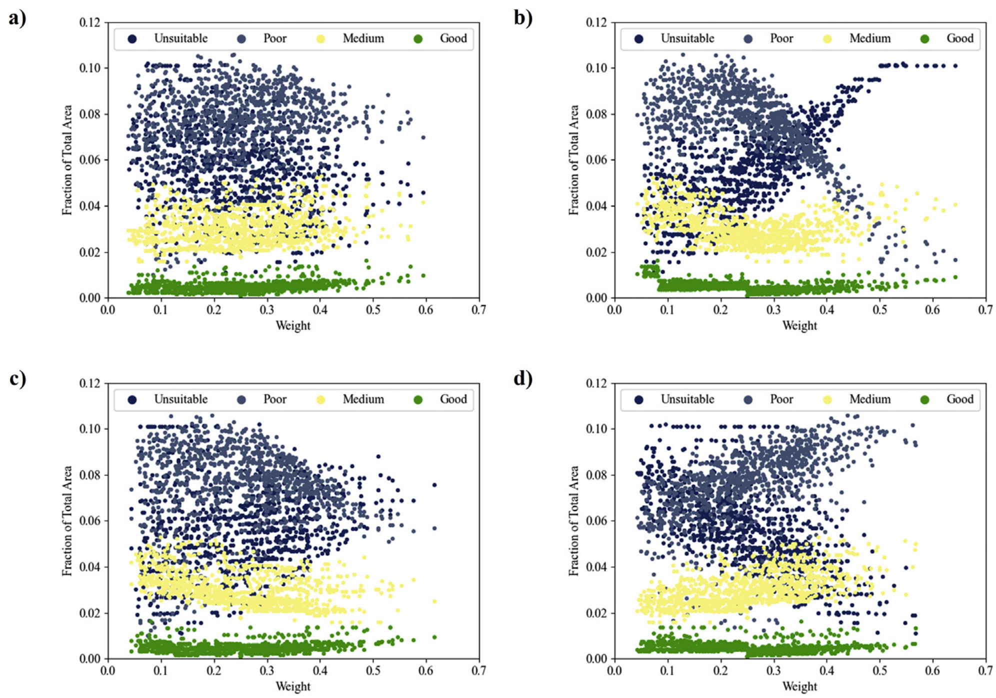

Fig. 8. The fraction of area for each of the output classification categories versus the weight of each input parameter: (a) slope, (b) soil quality, (c) distance to electrical infrastructure, and (d) land cover type.

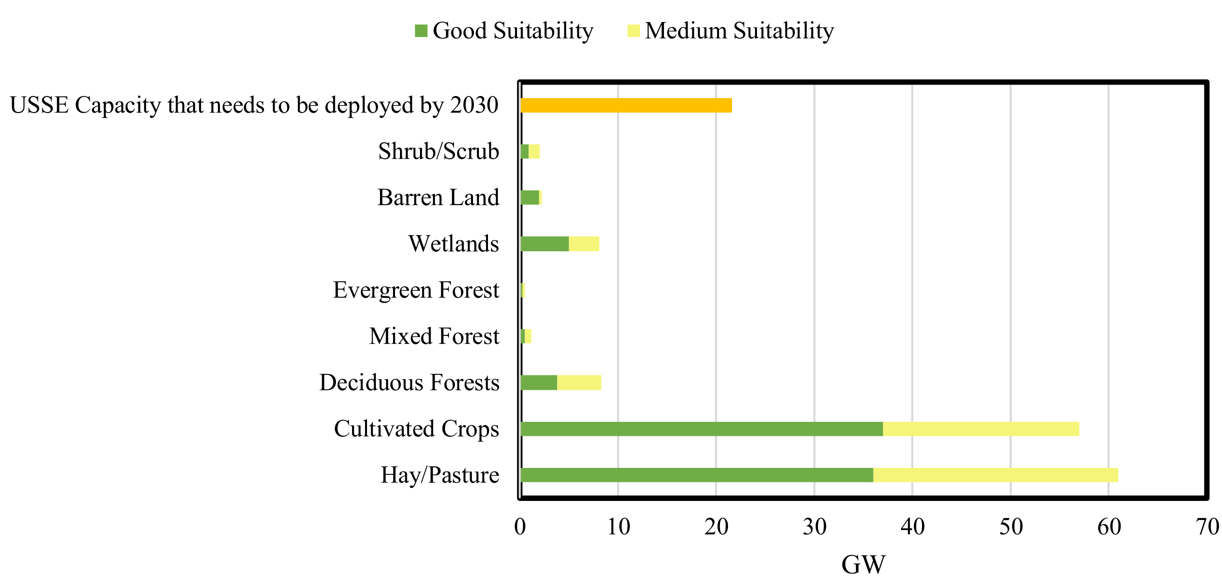

Fig. 9. Comparison of USSE capacity requirement for 2030 goals with the USSE potential of available good and medium suitability land in different land covers.

as a criterion for evaluating proposals for new USSE installations. The map (Fig. 10) depicts the county-wise distribution of the sum of good- and medium-suitability lands. Most counties have considerable potential for USSE development. Thus, there is an ample opportunity to avoid local concentration of USSE installations. However, more research is needed to define a threshold for USSE capacity and determine specific impacts that a high USSE concentration has on a local agriculture-dependent economy.

4.5.2. Incentivizing dual-use of agricultural lands and use of low soil-quality lands

As it is likely that agricultural land will be the prime target of future USSE installations, novel opportunities for dual-use of agricultural land should be explored. There is a growing body of literature that explores the opportunities for integrating renewable energy with ecosystem service enhancement. Hernandez et al. have summarized several synergies between solar development and ecosystem preservation; some of these synergies such as range-voltaics, which are intensive animal-solar energy systems, agri-voltaics, and solar development with soil restoration could be relevant for USSE development on agricultural lands in NYS [29,62]. Amaducci et al. simulated an agrivoltaic system in Italy; they found that the agrivoltaic system, consisting of solar panels several meters above the ground, improved soil water balance and increased

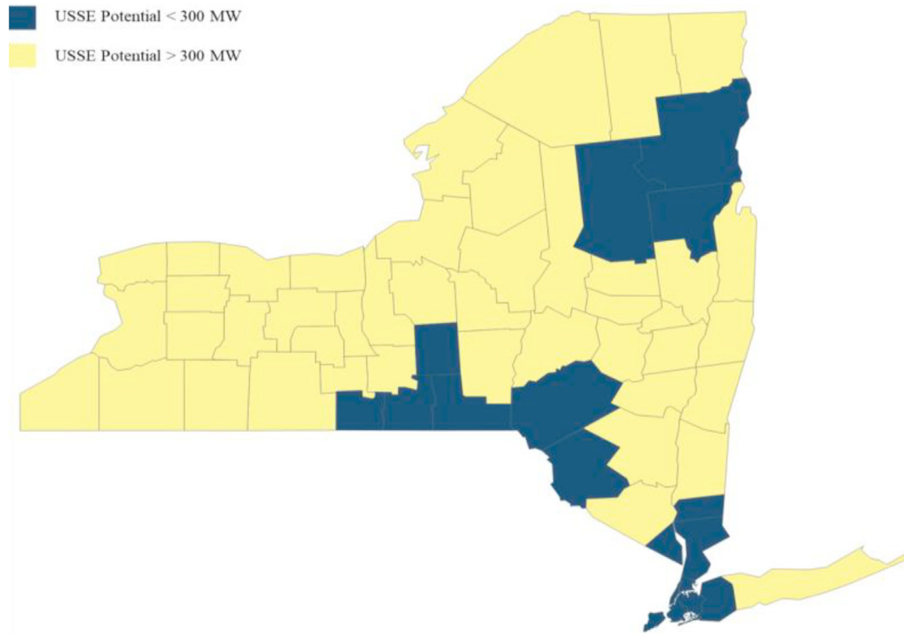

Fig. 10. County-wise distribution of USSE potential for USSE development on good and medium suitability land in NYS.

the yields of rain-fed maize [63]. Similarly, Semeraro et al. proposed a system to use the solar installations on agriculture land as green infrastructure to provide the ecosystem services of pollinator habitat and increased biodiversity, which in turn, can improve the crop yield on the farm [64]. State agencies involved with policy-making for solar development such as NYSERDA, the NYS Department of Environmental Conservation, and the NYS Department of Agriculture & Markets should consider exploring the NYS-specific incentives for agro-solar colocation.

Moreover, to mitigate the impacts of siting on agricultural lands, the use of low soil-quality land should be incentivized. USSE development should be directed to low soil-quality land as there is sufficient low soil-quality land available for USSE development. Only 23% of land occupied by current USSE installations is low soil-quality land — the use of prime farmland may compete with future food production, and it negatively affects public perception and increases opposition to USSE projects. According to this analysis, NYS has 73 GW of USSE potential on suitable agricultural lands that are not prime farmlands. Agricultural lands offer techno-economic advantages for USSE development, and by specifically incentivizing USSE development on non-prime farmlands, the social perception around such development could be improved.

4.5.3. Decision-making processes to encourage proactive community involvement

During the interactions with solar developers as well as during secondary research, we found growing public opposition to the development of USSE projects. Alleviating public concerns though community engagement is essential for sustainable growth of solar in NYS. Devising a decision-making approach that proactively involves the community can substantively help overcome the growing public opposition to USSE. During a preliminary analysis of land-ownership of USSE, it was found that more than 80% of land containing USSE installations is private land where developers usually sign a lease with respective private landowners before approaching the broader community. This decide-announce-defend approach is shown to arouse protective actions from the wider community [65]. In a decision-making model with proactive involvement of the community, the developer would approach the county or city/town instead of individual landowners to decide which land to consider before determining the best land for the proposed project. After determining suitable land with community representatives, the developer can negotiate the project size and location accordingly. NYS has recently passed the Accelerated Renewable Energy Growth and Community Benefit Act, which seeks to fast track all projects above 10 MW [66]. Although this law would allow for the identification of 'build-ready sites' by a number of state agencies, many siting decisions will naturally remain with private developers making them the key to success for NYS's renewable energy targets.

4.5.4. Limitations of USSE from a land-use perspective

Another important conclusion from this analysis is that NYS does not have a significant amount of land with the highest score in all four suitability criteria. The total USSE potential on such land, both agricultural and non-agricultural, is just 5 GW—not even sufficient for the 2030 goals, let alone the 2050 goals.

Moreover, non-agricultural good- and medium-suitability land (22.5 GW potential) is found to be barely enough to accommodate the USSE development that might be needed to achieve the NYS 70 by '30 goal (21.6 GW estimated requirement). At present, electricity accounts for just 13% of the State's total energy consumption [67]. Decarbonization inherently involves the electrification of the heating and transportation sectors; so, the future electricity requirement may be many-fold over this current estimated requirement. Therefore, if utility-scale solar is pursued for decarbonization goals, it could require the conversion of a significant area of agricultural lands for USSE installations.

5. Conclusion

This exercise was motivated by the need to characterize the impacts of utility-scale solar development on New York's land use, particularly on agricultural land, and to assess the potential for utility-scale solar development towards the realization of New York State's energy and decarbonization goals, specifically, the 70 by '30

goal. We employed a GIS-MCDA methodology, which is well-established for renewable energy land-use and siting analysis, at a spatial-resolution of 30m by 30m using criteria of protected areas, land cover, slope, distance from the electric substations, soil quality, and tree canopy percentage.

We aggregated and analyzed the spatial data for existing solar installations in the State to identify the USSE land-use trends in NYS and to inform the criteria for subsequent suitability analysis. Using land cover, slope, and protected areas for feasibility criteria, 46% of NYS's land (22,382 sq. miles) is feasible for solar development, representing a technical potential of 2235 GW. After defining suitability criteria, the land was classified as good, medium, poor, or unsuitable, and four scenarios were developed by increasing the number of additional development restrictions. The base case scenario has 2515 sq. miles of good suitability land (251 GW potential) and 6816 sq. miles of medium suitability land (680 GW potential).

A restriction on electrical infrastructure expansion did not have a significant effect on good-/medium-suitability land suggesting that electric infrastructure is well-distributed with adequate density across the state. Not employing the tree canopy percentage and contiguous areas conditions resulted in an overestimation of suitable land by as much as 83%.

We found that agricultural land accounted for 84% of the 140 GW combined potential on good- and medium-suitability land. The remaining 16% (22.5 GW) on non-agriculture suitable land is just sufficient for our estimated 2030 USSE requirement in NYS of 21.6 GW.

Considering that 40% of existing USSE footprints and 84% of model-estimated suitable land correspond to agricultural land, we infer that future solar development in the State will likely take place on agricultural land. The impact of USSE development on local agro-economies could be mitigated by regulating local concentrations of USSE installations. To mitigate the effects of land-use competition between crop production and solar development, policymakers should also explore state-specific synergies, such as agrivoltaics, and devise mechanisms to incentivize USSE development that enables the dual use of agricultural land. Our results show that the aggressive development of USSE towards New York State's goals will likely use considerable areas of agricultural land for USSE development. Thus, the role of USSE in the state's energy and decarbonization goals should be proactively planned.

For future work, we plan to further refine the model by incorporating electricity system data such as locational marginal price and transmission constraints that affect the revenue streams of solar farms. Moreover, in a cursory analysis, we observed that in a home-rule state, such as NYS, public opinions and local municipal planning play an outsized role in siting decisions, especially for utility-scale projects. We plan to investigate the role of local decision making and public acceptance on siting. From an agricultural impact perspective, we would like to explore how much farmland in a particular locality can be used for USSE before there are perverse impacts on the local agro-economy. Finally, we would also like to explore the colocation opportunities for solar on agricultural land that are specific to NYS and propose mechanisms to incorporate such synergistic opportunities into the evaluation process for siting decisions.

In the end, we would like to note here that, although this study focuses on New York state, with relevant modifications, the spatial model and general method of this study can also be utilized to study other geographic areas at different scales. The choice of criteria can change depending on the local conditions and the scale of the study area. E.g., for a larger area such as a county the data resolution might be coarser and some of the more regional criteria might not remain relevant. On the other hand, at a smaller scale such as cities, criteria such as zoning might hold a higher relevance. Also, as creating scenarios using a spatial model requires considerable spatial data, hence applicability of such modeling approach in a region with scant data availability might be limited.

CRediT authorship contribution statement

Venktesh V. Katkar: Conceptualization, Methodology, Investigation, Writing – original draft, Reviewing and Editing. **Jeffrey A. Sward:** Conceptualization, Methodology, Investigation, Writing – original draft, Reviewing and Editing. **Alex Worsley:** Methodology, Investigation, Writing – original draft. **K. Max Zhang:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2021.03.128.

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