Assessing Renewable Energy Potential on United States Marginal and Contaminated Sites

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Abstract

The United States has 121 million ha of marginal land that could be used to produce renewable energy. Approximately 1.73 million ha of this land includes federally funded brownfields, closed landfills, and abandoned mine lands. This study presents a GIS model to evaluate a range of site-specific energy production potentials on brownfields, closed landfills, and abandoned mine lands. Five energy sources are considered: soybeans, sunflowers, and algae for biodiesel, and solar and wind for electricity. Using soybeans, sunflowers, and algae, the United States could produce 39.9×10^3 TJ to 59.1×10^3 TJ of renewable fuel per year from biodiesel. Using solar and wind resources, the United States could produce 114 to 253 TWh per year of electricity. The lower end of the range for each resource represents marginal yields as expected under marginal conditions. The upper end of the range represents prime conditions and is used for comparison to other, more productive types of land and U.S. regional climates. While renewable energy sources sited on individual sites may produce marginal amounts of energy, strategic uses of land and combinations of sources can supplement the national energy matrix. The five renewable energy sources examined in this study could meet up to 39% of the total U.S. 2013 energy demand for biofuel and electricity.

Keywords: land use; contamination; renewable energy; geographic information systems (GIS); spatial analysis

1. Introduction

1.1. Motivation and Background

Recent studies have highlighted irreversible impacts of agriculture as well as direct and indirect land use change related to energy production [1–4]. Regarding biofuels, and ethanol in particular, Searchinger et al. (2008) found that inclusion of land use change in the life-cycle emissions from corn-based ethanol (a first-generation biofuel) results in a 93% increase in total greenhouse gas emissions (GHGs) in comparison to conventional gasoline [5]. The same calculation for switchgrass-based ethanol (a second-generation biofuel) results in a 50% total increase in GHGs compared to gasoline [5]. Microalgal biodiesel (a third-generation biofuel) shows promise for reducing GHGs [6,7]. However, like many biofuels, microalgal biodiesel can also exhibit positive or negative net energy results depending on cultivation and conversion pathways [8].

All biofuel feedstocks require nutrient inputs, water (often via irrigation), and suitable growing conditions [9]. Some feedstocks, however, are more resilient than others and can grow successfully on marginal lands. Peterson and Galbraith (1932) first defined marginal land as

“land on the margin of cultivation [...] the poorest land that can be remuneratively operated under given price, cost, and other conditions” [10]. Shortall (2013) considers three varieties of marginal land to be of particular importance: 1) land unfit for food production, 2) land of ambiguously lower quality, and 3) economically marginal land [11]. Milbrandt et al. (2014) describe marginal lands as abandoned, underutilized, and idle [12]. Nearly all definitions refer to poor physical and chemical soil properties and susceptibility to erosion [4,13–15]. Furthermore, there is a lack of knowledge regarding feasible and consistent energy crop yields on different types of marginal lands. This study evaluates brownfields, closed landfills, and abandoned mine lands as a subset of marginal lands available for renewable energy production.

Producing renewable energy on marginal lands, when done strategically and with regard to the entire life cycle, could potentially reduce the amount and intensity of inputs required for energy production. Scientific and legislative interest is growing in this area of land-constrained energy production, whether in the case of biofuel crops that can withstand poor soil quality and help meet energy mandates [11,12,16–19] or in the case of building renewable energy facilities on contaminated sites that would otherwise remain unused [12,20]. The U.S. EPA program: “RE-Powering America’s Land”, for example, encourages development of renewable energy projects on currently and formerly marginal and contaminated lands and provides resources to communities engaging in such projects [20]. Despite growing interest, previous studies have focused on bioenergy and have largely ignored non-agricultural sources, such as solar or wind [21–23].

Some studies claim that using marginal lands to produce bioenergy on a global scale is unfeasible for reasons such as the lack of economic incentives, disturbances to food security, and threats to biodiversity and conservation areas [3,24]. Other studies state that global feasibility estimates vary but marginal production levels become more viable when considered on the regional level [25]. Still others, as in this study, focus on symbiotic relationships between the land, regional characteristics, and the renewable energy potential available [26]. Every geographic and climatic region is different, and therefore spatial analyses are crucial to designing sustainable solutions for land use and for energy infrastructure systems [27]. A variety of energy production technologies can be employed. This study evaluates the energy that can be produced on marginal sites by cultivating soybeans, sunflowers, and algae for biodiesel, and by implementing solar and wind technologies for electricity.

2. Methods

One of the primary challenges in assessing the amount of marginal land available in an area is deciding what qualifies as “marginal” for the region being evaluated. While diverse definitions exist [10,14,17,28], marginal land is generally classified as land unfit for food-grade agriculture and not otherwise fulfilling conservational purposes or ecosystem services. This study limits consideration of marginal land to three types of marginal sites: brownfields, closed landfills, and abandoned mine lands (AMLs).

2.1. Land Data

The 48 contiguous states were mapped in the GIS program *ArcGIS 10*. Table 1 lists the sources and types of GIS data layers used in the analysis. Each of the three site types—brownfields, landfills, and abandoned mine lands—were imported as XY data and projected using the NAD83 datum. Since no polygon shapefiles were available, the area of each site was determined from existing databases. The AML site area was extracted from the Abandoned Mine

Land Inventory System (e-AMLIS) for each mine where the mine's status was listed as complete [29]. The site areas for closed landfills and brownfields were extracted from the EPA's RE-Powering database and matched by site name and location to the mapped points [30]. Figure 1 depicts the GIS process used to join the site data with the energy source data, resulting in energy production potentials on each site.

Table 1. GIS layers, data types, and sources for marginal sites considered in this study.

Figure 1. Overview of GIS process. Given energy sources and site locations, this process results in a range of spatially-based energy production potentials. Ovals represent map layers, organized by energy source and site type. Rounded rectangles represent GIS tools used to perform spatial analyses (here spatial joins). Energy sources in the first column are separated into agricultural feedstocks (bright green) and non-agricultural renewable resources (pink). Algae (yellow) is represented as both a feedstock and a non-agricultural resource as this research considers it to be grown under controlled conditions in a closed photobioreactor.

After removing sites with areas given as zero or null, 15,808 (of 18,738) brownfields, 588 (of 843) closed landfills, and 25,114 (of 50,483) abandoned mine lands remained. Table 2 summarizes the site areas, including minimum, maximum, mean, and total site areas before considering any energy siting options.

Table 2. Range of size of abandoned mine lands, brownfields, and closed landfills in the lower 48 states.

2.2. Modeling Feedstocks and Yields: Soybean, Sunflower, and Algae

Soybean, sunflower, and algae were evaluated as agricultural feedstocks on the brownfields, closed landfills, and AMLs. The GIS model used to calculate the microalgal growth rates on these sites was constructed in ModelBuilder in *ArcGIS 10*. ModelBuilder allows the user to automate complex GIS processes and describe geoprocessing procedures in a visual manner. To estimate the volumes of soybean and sunflower biodiesel, respectively, the product of four factors was computed: site areas, crop yields from USDA census records, oil content of the seeds, and harvest and conversion efficiencies [31]. Details of these calculations can be found in Appendix A. The lower 20% of USDA yields were used to model sunflower and soybean crop growth on contaminated sites. Low yields for sunflowers were assumed to range from 560 to 1,120 kg/ha (500-1,000 lb/acre) while low yields for soybeans were assumed to range from 1,010 to 1,340 kg/ha (15-20 bu/acre) [32]. No sites were eliminated due to excessive contamination. Different site types will lead to different yields due to soil conditions, e.g. soils on AMLs tend to be contaminated with heavy metals and the soils on brownfields are often acidic [33,34]. More research is needed to better characterize attainable crop yields on marginal and contaminated soils. Crop yields given here, while based on realistic conditions, are likely overestimates due to necessary site generalizations.

Algae yields were computed using ModelBuilder in *ArcGIS 10*. The rate of solar insolation was multiplied by a product of efficiency factors and divided by the lower heating value to obtain the microalgal growth rate. Details of this calculation can be found in Appendix A. Figure 2 shows the algae production rates, which are based on levels of solar insolation. This study uses the algae strain *Chlorella vulgaris* and assumes it is cultivated in flat-plate

photobioreactors (PBRs) [35,36]. The PBRs are assumed to occupy 80% of each suitable marginal site to allow space for access and maintenance. The PBR surface-to-volume ratio is $80.1 \text{ m}^2/\text{m}^3$, where 80 to $100 \text{ m}^2/\text{m}^3$ is considered optimal [35]. The PBR dimensions are 50 m long by 20 m high by 0.025 m wide. The growth rate was multiplied by the surface area of the PBR to determine the site-specific biomass production volume, which was converted to biodiesel volume using the density conversion of $870 \text{ kg microalgal biodiesel}/\text{m}^3$ biomass, 30% lipid content, and energy content conversion of $41 \text{ MJ/kg microalgal biodiesel}$.

2.3. Modeling Non-Agricultural Sources: Solar and Wind

Solar energy production is a natural extension of microalgal biodiesel production, and vice versa, as both processes require similar climatic conditions for optimal solar insolation. This study uses Global Horizontal Irradiance (GHI) to measure solar insolation. Measured in $\text{kWh}/\text{m}^2\text{day}$, GHI is defined as the sum of the direct normal irradiance (DNI) projected onto a horizontal surface plus the diffuse horizontal irradiance (DHI) [37]. GHI in the United States ranges from approximately 3.0 to $5.8 \text{ kWh}/\text{m}^2\text{day}$. This study assumes a utility-scale single-axis tracking photovoltaic (PV) system (0° tilt) with a standard efficiency range of 0.15 to 0.35 [38]. Figure 2 depicts the national PV potential under these conditions, which could be adjusted based on site-specific needs. Details of the PV power calculation can be found in Appendix A.

Figure 2. PV solar potential in $\text{GWh}/\text{m}^2\text{day}$ and algae growth rates in $\text{g}/\text{m}^2\text{day}$ on U.S. brownfields, closed landfills, and abandoned mine lands. PV system depicted assumed to have 0.35 efficiency rating and 5MW peak output.

Wind power ranges were mapped at the 50-m hub level, as shown in Figure 3, using state-based GIS layers compiled by NREL [38]. No data is available at the 50-m level for Alabama, Louisiana, Florida, and Mississippi, therefore these states were excluded from the wind analysis. Trends in turbine construction indicate that 80-m hub heights are becoming more common. In 2013, the average hub height was 80 m, which represents an increase of 45% since 1999 [39]. Analyses using 50-m hub levels likely result in an underestimate of the production potential since wind resources tend to increase with hub height, however the 50-m levels were retained in this analysis due to lack of geospatial wind data publicly available at the 80-m level.

Wind power was divided into classes according to the Wind Power Class (WPC) system [40]. WPC ratings range from 1 to 7, where $\text{WPC} \leq 2$ is considered marginal ($0\text{--}200 \text{ W}/\text{m}^2$) and 7 is considered superb ($800\text{--}2000 \text{ W}/\text{m}^2$). To estimate the national wind power potential, areas in m^2 of brownfields, closed landfills, and AMLs were multiplied by the WPC ratings and a typical capacity factor range of 0.25 to 0.40 [41,42]. Details of the wind power calculation and the Wind Power Class system can be found in Appendix A.

Figure 3. Range of United States wind power availability at the 50-m level. No data is publicly available at the 50-m level for Alabama, Florida, Louisiana, or Mississippi.

Both solar and wind technologies have two primary options regarding energy deployment: decentralized or “distributed” generation and grid-connected systems. Each comes with its own advantages and challenges. While electric generation potential is often abundant at the distributed level, solar and wind resources are often located in rural areas and far from high-demand urban centers [39,43]. Depending on the quality and intensity of solar insolation, it may

be economically favorable to build transmission lines from rural solar sources to urban power utilities. Alternatively, new generation facilities may be built closer to urban centers. Distributed PV systems may also be integrated into regional electric grids, especially as smart grids become more widespread. Transmission and distribution of electricity typically results in energy losses around 6% [44]. In addition, developers must prove the exhaustion of distributed options and the necessity of additional transmission lines before any new construction takes place [43]. Given a combination of distributed and grid-connected technologies, wind power capacity could reach 224 GW by 2030, up from 61 GW in 2013 [39]. Similarly, solar PV installations could total 302 GW by 2030, which would require a national installation rate of approximately 25-30 GW per year [43].

2.4 Mapping energy resources to marginal and contaminated sites

Minimum site areas may restrict the number of sites on which renewable energy projects can be implemented. Table 3 lists suggested minimum site areas for each renewable energy option and compares the minimum areas with number and size of sites currently available. Different sizes of solar and wind technologies are given in the table to demonstrate the ranges available. Taking the example of algae biodiesel in Table 3, the photobioreactors require at least one acre of land [45,46], of which there are approximately 21,000 sites, totaling 1.72 million ha of land. This area analysis is separate from the climatic analysis, which would suggest in this example to site algae facilities in areas of high solar insolation. Each additional analysis reduces the amount of land available for energy development.

Table 3. Number and area of marginal and contaminated sites that meet suggested minimum area requirements for renewable energy development.

Many permutations are possible to match the marginal and contaminated sites to respective energy crops and technologies. As previously mentioned, algae PBRs and solar PV systems should be sited in areas with high solar insolation, typically in the Southwest United States. Wind technologies should be sited in areas with the greatest wind resources, e.g. in the central region of the United States. Soybean and sunflower crops can be cultivated on sites with the least contamination and not better suited for solar and wind technologies. Soybean and sunflower crops also have the advantage of fitting small urban sites, whereas solar, wind, and algae technologies generally require larger pieces of land. Utility-scale technologies also require more land than decentralized or small-scale technologies. The calculations in this study focus on utility-scale development projects, while noting that the most comprehensive and sustainable energy solutions are likely to contain a mix of decentralized, mid-scale, and utility-scale projects.

3. Results and discussion

Brownfields, closed landfills, and AMLs are spread throughout the contiguous United States, however regional clusters do exist. Brownfields appear largely in the Northeastern and Mid-Atlantic states and extend toward the Midwest, with some notable clusters near the West Coast. Abandoned mine lands appear along the Appalachian Mountains in the East, Rocky Mountains in the West, and in other mountainous regions. Closed landfill sites are scattered across the entire United States.

Table 4 lists the total site areas nationally with the respective sunflower and soybean biodiesel production potentials. Biodiesel volumes were calculated based on a range of USDA

census data and marginal values from the literature [31,33,34,47,48]. Given a soybean biodiesel energy content of 35.9 MJ/L and a sunflower biodiesel energy content of 33.7 MJ/L, marginal and contaminated sites including landfills, brownfields, and AMLs could produce between 5.22×10^3 TJ and 10.4×10^3 TJ of sunflower biodiesel (40.9 - 78.6 MGY) or between 10.0×10^3 TJ and 13.3×10^3 TJ of soybean biodiesel (76.8 - 97.9 MGY). If half the sites were used for soybean biodiesel and the other half for sunflower biodiesel, the U.S. could produce 7.6×10^3 TJ to 11.8×10^3 TJ per year (61.4 - 85.8 MGY).

Table 4. Areas of contaminated sites and respective ranges of potential sunflower and soybean biodiesel production volumes.

Figure 2 illustrates the microalgal growth rates at each site according to solar insolation. The PBRs used to grow the algae are typically located in regions with plentiful solar insolation, such as in the Southwestern United States. Using microalgal growth rates greater than or equal to $16 \text{ g/m}^2\text{day}$ as a lower-efficiency bound, and utilizing sites of at least one acre in size to accommodate the PBRs, the United States could produce 2.25×10^6 tonnes of microalgal biomass per year on marginal lands. Given an energy content of 41 MJ/kg and lipid content of 30%, 2.25×10^6 tonnes is equivalent to 53.2×10^3 TJ per year or 1.50×10^9 L (396 MGY) of microalgal biodiesel [49]. Using microalgal growth rates greater than or equal to $18 \text{ g/m}^2\text{day}$ as a realistic upper efficiency bound, the U.S. could produce 821×10^3 tonnes of microalgal biomass per year. This is equivalent to 33.6×10^3 TJ or 950×10^6 L (251 MGY) of microalgal biodiesel. Considering economic, technical, and logistical feasibility, growth rates closer to $18 \text{ g/m}^2\text{day}$ are more likely to be implemented as they provide the greater return on investment.

For the case of solar power, this study assumes a utility-scale single-axis tracking PV system (0° tilt) with a standard efficiency range of 0.15 to 0.35 [50–52]. Given these specifications, the U.S. could produce 96.7 to 225 TWh/y of solar-based electricity. Total PV power production in a given geographic location is proportional to the size of the panel and the panel's peak output, both of which can vary considerably. Larger sites, or sites closer to densely populated areas, may benefit from larger networked systems.

When considering wind power, nearly half of the potential wind power sites examined in this study (46%) have a WPC that is considered marginal; 24% are ranked as “fair” and the remaining 30% have a ranking of “good” or better. To estimate the national wind power potential, the areas of brownfields, closed landfills, and AMLs were multiplied by the WPC ratings and a typical capacity factor range of 0.25 to 0.40 [41,42]. The U.S. could produce 18.1 TWh/y of wind-based electricity, using a 0.25 capacity factor on sites with fair to superb wind power ratings, to 27.5 TWh/y using a 0.40 capacity factor on sites with marginal to superb wind power ratings.

Table 5 summarizes the total potential biodiesel and electricity production if each energy source were produced on all mapped brownfields, closed landfills, and AMLs. Not all energy production methods will be used on all site types. Multi-criteria decision or optimization methods can be used to aid in energy site identification [53].

Table 5. Range of annual single-source energy production potentials on U.S. brownfields, closed landfills, and AMLs. Minimums and maximums are based on ranges of technological and environmental efficiencies. Each estimate of energy production assumes the use of all mapped marginal lands.

Trade-offs exist when pairing land and energy sources. Sites most conducive to growing sunflower or soybean, i.e. sites determined to have minimal contamination and a favorable growing climate, such as in the Eastern United States, will likely contribute to first- or second-generation liquid biofuels while the more heavily contaminated sites may be used for microalgal biofuels or solar- or wind-based electricity generation, where contamination levels and soil quality are less important. Solar and wind climatic conditions must also be favorable to implement non-agricultural technologies. In areas with both high solar insolation and less severe contamination, there is a trade-off between algae and solar production, and likewise between sunflower and soybean production. Some technology pairings are possible, e.g. wind farms and biofuel crops might be co-located on the same piece of land when cultivation and production conditions allow.

Conversion efficiencies affect the final production volumes. Biofuel conversion efficiencies vary widely depending on the feedstock and conversion pathway [54]. The agricultural feedstocks examined in this study have comparable conversion efficiencies. Sunflower oil has an average conversion efficiency of 93% [55] while soybean oil conversion efficiencies range from 90 to 98% [55]. Soybean and sunflower could be exchanged for more resilient crops, such as miscanthus or switchgrass, to maximize yields on contaminated soils. Microalgae conversion efficiencies can exceed 96% [56]. Depending on the specific technology employed, PV conversion efficiencies can range from 0.50 for residential systems to 0.95 for commercial systems [38]. Wind power conversion efficiencies can likewise reach 0.95 [57].

Renewable energy produced on contaminated sites can help satisfy the overall U.S. energy demand. In 2012, the U.S. consumed 1.20×10^5 TJ of biodiesel and 1.02×10^7 TJ of electricity (28.4×10^6 GWh) [58,59]. In comparison, the U.S. produced 64% of its combined biodiesel and electricity consumption in the same year from fossil fuels used to generate electricity alone. Given the five feedstocks and natural resources examined in this study, energy produced on contaminated sites could contribute up to 39% to the combined U.S. energy demand for biodiesel and electricity. The 39% estimate assumes wind turbines are installed on sites with a minimum 50-m wind density of 400 W/m^2 while solar installations and microalgal PBRs each occupy half of the sites with PV potential greater than $7.0 \text{ GWh/m}^2\text{day}$, corresponding to microalgal biomass growth rates greater than $18.0 \text{ g/m}^2\text{day}$. The remaining land is split equally between sunflower and soybean feedstocks. Fully realizing the 39% is unlikely, as it would be based on all technologies operating at optimal efficiency rates and at constant maximum capacity. Transportation logistics, technology implementation, and connection to the grid all need to be considered. These factors will reduce the total amount of energy available to the end user.

Not all contaminated land can or should be used for renewable energy development [60,61], nor should sites be completely abandoned following biofuel feedstock cultivation as this could lead to permanent land degradation [62]. Other uses can be sustainable and beneficial to the surrounding community. Such uses include urban food gardens [61,63,64], converted recreation areas [65], and commercial centers. The surrounding community should be consulted for development ideas to ensure the success and sustainability of the land reuse projects.

This study used brownfields, landfills, and abandoned mine lands to represent a subset of U.S. marginal lands. A broader marginal land analysis should ask what marginal land use scenarios represent the optimal use(s) of the respective lands and also produce the maximum volumes of desired types of renewable energy. Current land cover databases are limited in terms of soil quality recorded and spatial resolution of the data. In addition to lack of spatial data, there is also a lack of knowledge regarding feasible yields of energy crops on different types of marginal soils. Feedstocks such as camelina, switchgrass, and other perennial grasses could grow well in low-quality soils.

Availability of water needs to be considered for sunflower, soybean, and algae cultivation. While it can be expected that many sites in this study have some access to water given the nature of their former uses as industrial sites, actual access will vary based on geographic location and project specifications. Algae-producing facilities can collaborate with wastewater treatment plants to reuse treated wastewater, which also provides necessary nutrients for algae growth [56,66]. Some irrigation is possible for sunflower and soybean sites, however the environmental and economic benefits of growing crops on these sites should exceed the respective costs of any irrigation for the projects to be sustainable. Out of the five renewable energy crops and technologies presented here, projects involving sunflower and soybean biodiesel crops will likely be most sensitive to water availability since water deficiency directly impacts oilseed production [67]. Further research is needed to better understand the efficiency and sustainability of on-site irrigation practices [68]. By optimizing the site type, energy source characteristics, and regional needs, marginal lands and contaminated sites can play an increasingly important role in meeting United States energy demands.

4. Conclusion

This study constructed and implemented a GIS model to evaluate a range of site-specific energy production potentials on brownfields, closed landfills, and abandoned mine lands. Five energy sources were considered: soybeans, sunflowers, and microalgae for biodiesel, and solar and wind for electricity. When all five resources on all three site types are allocated for optimal performance, energy produced on contaminated lands could help satisfy up to 39% of the total U.S. demand for diesel and electricity. Trade-offs do exist when pairing land and energy sources: microalgae and solar production facilities will likely compete for the same land, as will sunflowers and soybeans. Technology pairings can create opportunities for increased energy production, especially in the case of co-located wind farms and biofuel crops. Not all available land should be used for energy production; alternative uses include, for example, community-initiated food gardens and recreation areas. Logistics such as transportation, transmission lines, and access to water and other nutrients also need to be considered. Optimal use of land, feedstocks, and energy production technologies will allow contaminated lands to play an increasingly vital role in fulfilling United States energy demands in a sustainable manner.

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APPENDIX A. DETAILED STEPS FOR ENERGY CALCULATIONS

Assessing Renewable Energy Potential on United States

Marginal and Contaminated Sites

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Appendix Contents

Appendix A presents the energy calculations performed in the analysis of brownfields, closed landfills and abandoned mine lands across the lower 48 United States. Data for brownfields and closed landfills were extracted from the EPA's RE-Powering database while mine lands data was extracted from the Abandoned Mine Land Inventory System (e-AMLIS). All data calculations were performed in Microsoft Excel and ArcGIS 10.

A1.		Conversion	factors
A2.	Sunflower	yield	calculations
A3.	Soybean	yield	calculations
A4.	<i>Chlorella vulgaris</i> :	Microalgal composition and growth rates	

A5. Photovoltaic calculations

A6. Wind turbine calculations at 50 m

A1. CONVERSION FACTORS

Table A.1 presents physical conversion factors used in the energy calculations presented in Appendix A. Feedstock-specific factors and the relevant references are noted in each sub-appendix (A.2-A.6).

Table A.1. Conversion factors for physical constants used in the energy production calculations

A2. SUNFLOWER YIELD CALCULATIONS

The volume in gallons of sunflower biodiesel, $V_{sunflowerBD}$, was calculated as shown in Eq.

(A.1):

$$V_{sunflowerBD} = \frac{2.20462}{2.471} \cdot \frac{A \cdot Y_{kg} \cdot L_p \cdot C}{\rho} \quad \text{Eq. (A.1)}$$

where

A = total area in acres of each marginal site type across the 48 contiguous states

Y_{kg} = yield in kg seed/ha

L_p = fractional percentage of oil in seeds = 0.39 for marginal yields in this study [1]

C = conversion efficiency of oil to biodiesel = 0.99 for sunflower [2]

ρ = density of sunflower biodiesel at 15.5° C = 0.880 kg/L (7.34 lb/gal) [3]

2.20462 = lb/kg conversion

2.471 = acres/ha conversion

A3. SOYBEAN YIELD CALCULATIONS

The volume in gallons of soybean biodiesel, $V_{soybeanBD}$, was calculated as shown in Eq. (A.2):

$$V_{soybeanBD} = \frac{A \cdot Y_{bu} \cdot L_{bu} \cdot C}{\rho}$$

Eq. (A.2)

where

A = total area in acres of each marginal site type across the 48 contiguous states

Y_{bu} = yield in bushels/acre [4]

L_{bu} = oil content of seeds in lb oil/bushel [5,6]

C = conversion efficiency of oil to biodiesel = 0.96 for soybean [7]

ρ = density of soybean biodiesel at 15.5° C = 0.884 kg/L (7.37 lb/gal) [3]

A4. *CHLORELLA VULGARIS*: MICROALGAL COMPOSITION AND GROWTH RATES

The microalgal growth rate (Eq. A.3) for the strain *Chlorella vulgaris* was calculated using the strain's lower heating value 41 MJ/kg [8,9] and adjusted for a range of efficiency factors (Table A.2). The growth rate was converted to biodiesel and energy production volumes using the density conversion

870	biodiesel	kg/m ³	biomass.

Table A.2. Efficiency factors affecting microalgal growth

To calculate the geo-specific microalgal growth rate, R , the GIS layer of energy production facilities and the GIS layer of solar insolation values were spatially joined so that both sets of data would be accessible in one database table, thus enabling a more efficient calculation procedure. Eq. (A.3) describes how R was calculated.

$$R = \frac{S \times P}{H} \quad \text{Eq. (A.3)}$$

where

R = microalgal growth rate in (g biomass)/(m²day)

S = solar insolation as location-specific global horizontal irradiance (GHI) in MJ/(m²day)

P = product of efficiency factors = 0.086 for this study (See Table A.2.)

H = lower heating value = 41 MJ/kg biomass for *Chlorella vulgaris*

A5. PHOTOVOLTAIC CALCUATIONS

The potential annual electricity (E) produced by utility-scale PV systems was calculated via Eq. (A.4):

$$E = 365 \cdot A \cdot I \cdot \eta \quad \text{Eq. (A.4)}$$

where

A = area of PV surface in m²

I = solar insolation as location-specific global horizontal irradiance (GHI) in kWh/m²day

η = efficiency = 0.15 to 0.35 [13]

365 = days/year

A6. WIND TURBINE CALCULATIONS AT 50 M

Eq. (A.5) describes the calculation of wind power availability in this study. The 50-m wind power density, based on the respective Wind Power Class (Table A.3), was multiplied by the turbine capacity factor, the installed power density, and the conversion efficiency to obtain the potential wind resource availability at 50 m.

$$W = 8,760 \sum_{i=1}^n c_i \cdot f \cdot \eta \cdot d$$

EQ. (A.5)

1.0

where

W = wind resource availability at 50 m

i = site number

n = total number of sites

c_i = wind power density based on wind power class (See Table A.3.)

f = wind turbine capacity factor = 0.25 to 0.40 [14,15]

η = conversion efficiency = 0.95 [13]

d = installed power density = 5 MW/km² [14]

8,760 = hours/year

Table A.3. Wind power class, density, and description at 50 m. All wind power classes span two density categories. Table adapted from [16,17].

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Table A.2. Conversion factors for physical constants used in the energy production calculations.

Starting Unit	Unit	Target	Conversion factor
lb		kg	2.20462
			lb/kg
acres		ha	2.471
			ac/ha
hours/day		hours/ye	8,760
	ar		h/y

Table A.3. Efficiency factors affecting microalgal growth

Efficiency factor	alue
Photosynthetic efficiency	.267
Losses due to reflection ^a	.95
Losses due to PBR geometry ^b	.99
Photon utilization efficiency ^c	.50
Biomass accumulation efficiency ^d	.72
Harvesting recovery rate ^e	.95
Product of efficiency factors	.086

^a Assuming PBR constructed from HDPE

^b PBR tilted at 80 degrees

^c[10]

^d[11]

^e [12]

Table A.4. Wind power class, density, and description at 50 m. All wind power classes span two density categories. Table adapted from [16,17].

Wind Power Class	Wind Power Density at 50m (W/m^2)	Description
1	0	N/A
2	200	negligible
3	300	marginal
4	400	fair
5	500	good
6	600	excellent
7	800	outstanding
	2000	superb

Table 1. GIS layers, data types, and sources for marginal sites considered in this study.

Site type	GIS data source	Data type	Year
Brownfield	EPA ACRES database	Point	2013
Landfill	EPA Landfill Methane Outreach Program	Point	2013
AML	OSMRE Abandoned Mine Land Inventory System	Point	2012

Table 2. Number and size of abandoned mine fields, brownfields, and closed landfills in the lower 48 states.

Site type	Number of sites	Minimum site area (ha)	Maximum site area (ha)	Mean site area (ha)	Total site area (ha)
AMLs	25,114	0.004	91,459	57.8	1,730,030
Brownfield	15,808	0.004	323,742	67.4	1,066,521
Closed landfills	588	0.405	890	36.4	21,443

Table 3. Number and area of marginal and contaminated sites that meet suggested minimum area requirements for renewable energy development.

Energy source	Minimum site area required (ac)	Minimum site area required (ha)	Number of qualifying sites based on area	Total qualifying site area (ha)
Sunflower	0.01 ^a	0.005	29,931	1,730,031
Soybean	0.01 ^a	0.005	29,931	1,730,031
Algae PBR	1 ^b	0.404	21,060	1,728,820
Solar PV: decentralized	0.01 ^c	0.005	29,931	1,730,031
Solar PV: utility-scale	40 ^c	16.2	6,617	1,681,862
Wind: decentralized	0.25 ^c	0.101	25,906	1,729,826
Wind: 1-2 turbines	2 ^c	0.809	17,112	1,726,833
Wind: utility-scale	100 ^c	40.5	4,225	1,619,621

^aNiblick et al. (2013).

^bAdapted from U.S. DOE (2010) and Menetrez (2012).

^cU.S. EPA (2013).

Table 4. Areas of contaminated sites and respective ranges of potential sunflower and soybean biodiesel production volumes.

Site type	Area (ha)	Sunflower Biodiesel (10 ⁶ L) min-max yields	Soybean Biodiesel (10 ⁶ L) min-max yields
Landfill	28,116	2.8	5.0
		5.6	6.7
Brownfield	14,918	1.4	2.6
		2.9	3.5
AML	1,505,252	150	270
		301	360

Table 5. Range of annual single-source energy production potentials on U.S. brownfields, closed landfills, and AMLs. Minimums and maximums are based on ranges of technological and environmental efficiencies. Each estimate of energy production assumes the use of all mapped marginal lands (1,066,521 ha brownfields, 21,443 ha closed landfills, and 1,730,030 ha AMLs).

Source	Biodiesel (min) (TJ)	Biodiesel (max) (TJ)	Electricity (min) (GWh)	Electricity (max) (GWh)
sunflower	5,219	10,439	N/A	N/A
soybean	10,028	13,305	N/A	N/A
algae	33,663	53,216	N/A	N/A
solar	N/A	N/A	96,778	225,815
wind	N/A	N/A	18,139	27,571

fig. 1

fig. 2

fig. 3