Renewable and Sustainable Energy Reviews 60 (2016) 489–497

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessing renewable energy potential on United States marginal and contaminated sites

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ARTICLE INFO

Article history:
Received 19 March 2015
Received in revised form
2 July 2015
Accepted 1 December 2015

Keywords:
Land use
Contamination
Renewable energy
Geographic information systems (GIS)
Spatial analysis

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–59.1×10^3 TJ of renewable fuel per year from biodiesel. Using solar and wind resources, the United States could produce 114–53 TW h 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.

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http://dx.doi.org/10.1016/j.rser.2015.12.045
1364-0321/

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. [5] 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 [10] 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 [11] 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. [12] 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]. Fig. 1 depicts the GIS process used to join the site data with the energy source data, resulting in energy production potentials on each site.

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.

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 1120 kg/ha (500–1000 lb/acre) while low yields for soybeans were assumed to range from 1010 to 1340 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

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