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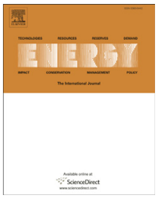

Optimal grid design and logistic planning for wind and biomass based renewable electricity supply chains under uncertainties

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ABSTRACT

In this work, the grid design and optimal allocation of wind and biomass resources for renewable electricity supply chains under uncertainties is studied. Due to wind intermittency, generation of wind electricity is not uniform and cannot be counted on to be readily available to meet the demand. Biomass represents a type of stored energy and is the only renewable resource that can be used for producing biofuels and generating electricity whenever required. However, amount of biomass resources are finite and might not be sufficient to meet the demand for electricity and biofuels. Potential of wind and biomass resources is therefore jointly analyzed for electricity generation. Policies are proposed and evaluated for optimal allocation of finite biomass resources for electricity generation. A stochastic programming model is proposed that optimally balances the electricity demand across the available supply from wind and biomass resources under uncertainties in wind speed and electricity sale price. A case study set in the American Midwest is presented to demonstrate the effectiveness of the proposed model by determining the optimal decisions for generation and transmission of renewable electricity. Sensitivity analysis shows that level of subsidy for renewable electricity production has a major impact on the decisions.

1. Introduction

The U.S. is the world's leading energy consumer with fossil fuels accounting for 83% of the energy supplied to the economy in 2012 [1]. Electricity generation consumes the largest share (i.e. 40%) of the U.S. energy resources [1]. There is growing public awareness that consumption of fossil fuels in large amounts is contributing to global warming by releasing increasing quantities of GHG (greenhouse gas) emissions [2]. In addition, extraction of large quantities of coal, natural gas, and crude oil are leading to faster depletion of the finite reserves of fossil fuels. The depletion of fossil fuels is likely to result in price fluctuations, uncertainties in the energy supply chain, and social upheavals due to job losses [1]. Renewable energy sources have the potential to cost-effectively satisfy a large portion of U.S. electricity needs, while at the same time safeguarding the environment, and reducing dependence on fossil fuels [3,4]. Research indicates that if optimally utilized, renewables can contribute up to 20% of total U.S. electricity generation by 2030 [4,5].

In 2012, 11% of the electricity generated in the U.S. was produced from renewables [1]. Hydropower generated the maximum share of 7% while the contribution of wind and biomass was 2% and 1.4% respectively [1]. The share of hydropower is not expected to increase as the hydroelectric resource has plateaued out with most of the promising large-scale hydropower sites in the U.S. already being tapped for electricity generation [1].

Wind energy is one of the highest potential renewable resources currently available for electricity generation in the United States [1,4]. The estimated onshore wind energy has the annual potential to generate 5 million GWh of electricity [4]. In the U.S. wind power was used to generate 90,000 GWh of electricity in 2012 [1], representing 23% of generation from renewables [4]. Even though wind generated electricity currently makes up only 2% of total U.S. electricity generation, wind power has grown at a 25% annual rate (from 2001 to 2010) and represents 35% of all new generating capacity [1]. Onshore wind technology is generally considered to be commercially available in the U.S [4].

Currently there are some challenges that prevent a wide spread deployment of renewable electricity generated from intermittent

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resources like wind energy, although there are some works that indicate that the wind resource is a periodical phenomenon [6] that can be estimated, and this intermittency is attenuated in large areas [7]. Wind intermittency is perceived as an obstacle to the integration of wind generated electricity into the existing power grid [1,8]. The biggest challenge is how to efficiently and economically supply electricity from diverse and dispersed wind farm sites to faraway electricity demand markets [8]. In the United States, most of the highest wind energy potential is located in the sparsely populated Midwestern states. However, highest demand for electricity is located in the densely populated urban areas of the Northeast, Southern California, and few major cities in the Midwest and Rocky Mountains [1].

Research on optimizing of a WESC (wind based renewable electricity supply chain) is extensive [9]. Research by Refs. [10–13] proposes stochastic optimization models that consider uncertainties in wind speeds, electricity demand and/or electricity sale price. A growing body of literature [14–26] also addresses the intermittency of wind in conjunction with energy storage mediums i.e. pumped water [10,19,20,24,25], compressed air [21,26], deep-cycle batteries [22], etc. or traditional readily dispatchable electricity generators i.e. hydropower or natural gas fired. However, none of the currently available electricity/energy storage technologies are economically and efficiently capable of providing long-term power storage without significant conversion losses [23,27].

Research is emerging on study of WESC optimization where the wind intermittency is balanced by another renewable resource like solar energy [22,28–30], but none of them incorporates the stochastic characteristics of the system inputs, solar radiation, wind speed, and electricity demand. Recently work by Ref. [22] studies a hybrid solar and wind energy system where wind intermittency is balanced by the use of solar power. An optimization model is proposed that considers uncertainty in wind speeds and solar radiation. However, the use of multiple non-dispatchable renewable resources (i.e. solar and wind) is unlikely to eliminate the need of a readily dispatchable resource of electricity (e.g. natural gas fired generators) as a back-up [31].

Biomass resources represent a type of “stored” energy that can be used as feedstock to generate electricity whenever required and can act as a dispatchable resource for electricity generation without the use of a fossil-fuel resource as a back-up. Recent studies [32] have highlighted the potential availability of a billion tons per year of biomass for energy production including electricity and liquid transportation fuels. In 2012 an estimated 63,000 GWh was generated in the U.S. using biomass as feedstock [1], which represents 16% of generation from renewables [4]. Combustion technologies used to convert biomass to electricity are generally considered commercial [32]. Biomass procurement and feedstock quality are the key cost drivers that impact the cost of bioelectricity [33]. Currently, biomass is the only renewable source that can be used to generate both electricity and produce liquid transportation fuels [5,32]. The amount of biomass resources are finite and might not be sufficient to meet the demand for both electricity and biofuels in the U.S. due to the production mandates of the federal Renewable Fuel Standard [1]. Accurate estimates for bioelectricity generation potential are difficult to obtain but are estimated to be around 1.4 million GWh annually if 40% of the available biomass is used for electricity generation [1].

This research aims to leverage the use of available wind and biomass resources for sustainable renewable electricity generation and transmission. Renewable energy policies are proposed for the optimal allocation of finite biomass resources for electricity generation. Each policy is evaluated across the economic objective (i.e. profit maximization) to select the optimal allocation ratio(s). The work also studies the design of an optimal grid infrastructure (from power production to transmission) that can integrate renewable electricity generated from wind and biomass resources into the power grid under uncertainties in wind speeds [34]. To increase the supply and reliability of electricity generated from renewables it is necessary to upgrade the transmission lines (if they exist) between supply and demand zones so as to be able to cope with the additional electric load to be carried by the power grid [4,8]. Upgrading the transmission capacity will result in significant cost [35]. If no transmission lines are available between the electricity supply and demand zones, costly new transmission lines should be established [8,35].

The unique contribution of this study is incorporating economic viability while optimizing a WBBRESC (wind and biomass based renewable electricity supply chain) by considering constraints on biomass availability, uncertainties in wind speed and electricity sale price. In this work wind energy is considered as the primary renewable resource for electricity production and wind farms are referred to as the “base-load” generators used for meeting a ratio of the off-peak electricity demand. Biomass is considered as the secondary renewable resource for electricity production and a BMPP (biomass power plant) is referred to as the “on-demand” generator used to compensate for shortage in electricity supply from wind farms due to wind intermittency. To the best of our knowledge this is the first research effort to study the optimal design of a WBBRESC that also considers the grid network and transmission capacities.

A two-stage SMILP (stochastic mixed integer linear programming) model is proposed that ensures the financial viability by balancing the electricity demand across the available supply from wind and biomass resources under uncertainties in wind speed and electricity sale price. The potential of wind energy, intermittency of wind electricity generation systems, biomass resource availability, electricity demand, and electricity sale price are used as constraints in the proposed model. The model integrates all the supply chain logistics for generation and transmission of renewable electricity to arrive at optimal decisions that include: 1) site selection for installation of wind farms, BMPPs, and grid stations; 2) generation capacity of wind farms and BMPPs; 3) grid connectivity; 4) transmission capacity of power lines; and 5) amount of renewable electricity to be supplied to demand zones.

A case study is used to demonstrate the effectiveness of the proposed SMILP model by optimally allocating the available wind and biomass resources for generating and transmitting up to 20% of the off-peak electricity demand of a U.S. Midwestern region by 2030. Sensitivity analysis is conducted to measure impact of renewable energy policy (i.e. subsidy level for renewable electricity generation) on the profit and the supply chain logistic decisions.

2. Problem statement

This research studies an integrated WBBRESC. A list of indices, parameters, and decision variables are given in Appendix A. The conversion factors from the U.S. customary units to the metric units (SI (International System of Units)) are given in Appendix B. This paper assumes that: 1) only road haulage is considered for the transportation of biomass; and 2) the off-peak electricity requirement is known and proportional to the population in each demand zone.

The major logistics activities in a WBBRESC are shown in Fig. 1. Wind farms can be established in renewable electricity supply zone *r*. The generation capacity of wind farms is driven by the off-peak demand for renewable electricity, while the amount of electricity produced is limited by the availability of wind (of sufficient speed)

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