Renewable Energy 91 (2016) 207–223

Contents lists available at ScienceDirect

Renewable Energy

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

The role of bio-renewables in national energy and transportation systems portfolio planning for low carbon economy

Venkat Krishnan*, [1], James D. McCalley

Electrical and Computer Engineering Department, Iowa State University, Ames, IA 50014, USA

A R T I C L E I N F O

Article history:
Received 23 March 2015
Received in revised form
28 December 2015
Accepted 17 January 2016
Available online xxx

Keywords:
Bio-power
Biofuels
Feedstock
Energy infrastructure planning
Environmental impacts

A B S T R A C T

Bio-power and biofuels are promising alternative energy resources. This paper investigates their role in the long-term U.S. national energy and transportation portfolio planning, while considering the competition among other energy options. The paper presents a systematic modeling framework for integrating biomass pathways to the energy and transportation systems, and also captures the geographical variation in the feedstock availability and cost across the U.S. The paper then presents two different case studies-energy sector planning and integrated energy & transportation sectors planning. The studies reveal long-term cost and emission savings from bio-renewables, where the bulk of benefits are observed due to biofuels (with bio-power production limited by feedstock prices). Under a 40% CO_2 emissions reduction scenario over the next 40 years, penetration of bio-renewables promise up to 10-Trillion USD (2010$) savings in system costs (investments and operational). Simulations also show that the impediment with bio-renewable penetration is mostly influenced by the availability of low-cost feedstock, specifically for bio-power production. According to current estimation of long-term feedstock availability, U.S will be able to power upto 150 Billion Gallons Year (BGY) (or approx. 560^*10^9 L per year) bio-refinery capacity around 2020s, and about 200 BGY (or approx. 750^*10^9 L per year) by 2050.

1. Introduction

Energy generation by fossil fuel combustion is one of the major contributors to the anthropogenic carbon-dioxide (CO_2) emissions leading to global warming concerns. In the U.S., CO_2 emitted by burning fossil fuels such as coal, gas and petroleum for electricity generation, transportation and other (industrial, residential and commercial) purposes contributed to about 79% of the total national greenhouse gas (GHG) emissions on CO_2 equivalent (CO_2e) [1], of which electricity generation (~41%) and transportation (~33%) have been the two major sources. In this context, long-term planning efforts towards low carbon emissions in the electricity sector have been mainly in terms of integrating variable renewables and addressing the associated system flexibility needs [2], rendering the fossil-fired power plants clean using carbon capture and emission control devices [3], and designing market policies to penalize emissions [4]. In the transportation sector, efforts have been towards using alternative fuels such as natural gas, hydrogen, ethanol, and electricity [5,6]. Acknowledging the perspective that the path towards success would comprise all the available solution strategies, this paper explores the role of biomass based renewable products (also known as bio-renewables, namely biofuels and bio-power) in decarbonizing and sustaining the future economy [7].

Biomass feed-stocks subject to thermo-chemical and bio-chemical conversion processes have tremendous potential to supply bio-power and biofuels at a highly reduced emissions rate [8–10]. This emission savings is possible because agriculture- and forestry-based biomass feed-stocks facilitate sequestering carbon from the environment during their growth, and hence an integrated study of biomass with other sectors reveal the existence of near net-carbon-zero pathways across the entire energy production-transportation-conversion-consumption cycle [9]. Assessments [11] do indicate that significant emission savings can be ensured by following sustainable practices at the biomass production and processing stages, such as choosing the best feedstock, geographical location, land-use practices, agro-chemical uses, feedstock drying and transportation means. Furthermore, to circumvent issues related to food supply and to increase the economic viability, pathways involving secondary feed-stocks (residues and energy crops) and genetically modified crops (with high growth rate & energy content) are pursued.

* Corresponding author.
E-mail address: venky83krish@gmail.com (V. Krishnan).
[1] Currently at National Renewable Energy Laboratory (NREL), Golden, CO 80401, USA.

http://dx.doi.org/10.1016/j.renene.2016.01.052
0960-1481/

Nomenclature

t, z time period
i, j energy sector nodes (at regional scale) and arcs (representing various components, e.g., generators, transmission lines).
x, y transportation sector nodes (at state level) and arcs, e.g., pipelines, interstate passenger transportation
k commodity transported ($k = ek$ is coal or biomass for energy; $k = fk$ is non-energy freight; $k = p$ is passengers)
m interstate transportation mode (fleet or vehicle type)

Decision variables
$e_{(i,j)}(t)$ energy flow in the arc (i,j) at time t
$e^s_{(i,j)}(t)$ energy flow through arc (i,j)'s supply curve segment s at time t
$p_{(i,j)}(t)$ number of LDVs of type i in region j at time t
$f_{(x,y,k,m)}(t)$ number of interstate vehicles of type m to transport commodity k across arc (x,y) at time t
$eInv_{(i,j)}(t)$ investment in infrastructure (i,j) at time t
$pInv_{(i,j)}(t)$ investment in LDV i at time t
$fInv_{(x,y,m)}(t)$ fleet investments of type m across transportation arc (x,y) at time t

Parameters and constants
$CostOp_{(i,j)}(t)$ operational cost of energy commodity in \$/unit-commodity (e.g., \$/GWh or \$/kiloton or \$/gallon) through arc (i,j) at time t (where 1 gallon ≈ 3.78 L)
$CostOp^s_{(i,j)}(t)$ operational cost of energy commodity in \$/unit-commodity through arc (i,j)'s supply curve segment s at time t
$CostOp^p_{(i,j)}(t)$ operational cost of LDV i in \$/vehicle in region j at time t
$CostOp_{(x,y,k,m)}(t)$ operational cost of transportation by interstate mode m in \$/vehicle-mile to transport commodity k across arc (x,y) at time t
$CostInv_{(i,j)}(t)$ investment cost in \$/unit-capacity for arc (i,j)
$CostpInv_{(i,j)}(t)$ investment cost of LDV i in \$/vehicle in region j at time t
$CostfInv_{(x,y,m)}(t)$ investment cost of mode m in \$/vehicle across arc (x,y) at time t
r discount rate
$\eta_{(i,j)}, \eta_{(x,y,k,m)}$ arc efficiency parameters
$d^e_j(t)$ nodal energy demanded (electricity, petroleum, or gas) at region j at time t.
$d^{eT}_j(t)$ nodal energy demand (fuel or electricity) imposed by transportation systems in region j at time t.
$d^{pT}_j(t)$ LDVs demanded in region j at time t
$d^T_{(x,y,k)}(t)$ Interstate transportation demand for commodity k across arc (x,y) at time t (bi-directional quantity); where $k = fk$ is non-energy freight demand and $k = p$ is passenger demand
$h_{ek}(t)$ energy content of the energy commodity ek (coal or biomass) in GWh/kiloton
$\alpha^j_{(x,y)}$ proportion of energy for bi-directional transportation across arc (x,y) coming from region j
$fuelC_m(t)$ fuel/energy consumption by mode m, (e.g., gallon/vehicle-mile or GWh/vehicle-mile) at time t
$l^p_{(i,j)}(t)$ average miles traveled by LDV i in region j
$l_{(x,y)}(t)$ distance between states x and y in miles
$lbe_{(i,j)}(t), ube_{(i,j)}(t)$ lower and upper existing capacities (accounts periodic retirements for infrastructures) of energy arc at time t
$ube^s_{(i,j)}(t)$ Upper bound on the supply curve's segment s
$cap\_e_{(i,j)}(t)$ total arc capacity at time t, including existing capacity and new investments
$lbeInv_{(i,j)}(t), ubeInv_{(i,j)}(t)$ minimum and maximum limits on infrastructure investments at time t
$ubp_{(i,j)}(t)$ Upper bound on the LDV i existing fleet
$cap\_p_{(i,j)}(t)$ total LDV i fleet size in region j at time t, including existing size and new investments
$lbpInv_{(i,j)}(t), ubpInv_{(i,j)}(t)$ minimum and maximum limits on LDV i investments at time t
$lbf_{(x,y,m)}(t), ubf_{(x,y,m)}(t)$ lower and upper interstate fleet capacity for mode m across arc (x,y) at time t
$cap\_f_{(x,y,m)}(t)$ total capacity for mode m across arc (x,y) at time t, including existing size and new investments
$lbfInv_{(x,y,m)}(t), ubfInv_{(x,y,m)}(t)$ minimum and maximum limits on mode m investments across arc (x,y) at time t
inv_start investment starting period
$life, plife, flife$ infrastructure lifespan (electric, LDV and interstate fleet) in years
$I(t\text{-}z \leq life)$
indicator function on available life of an infrastructure (applies to $plife$ and $flife$ also)

Given the above background, this paper investigates the national scale potential of bio-renewables to compete with and complement other energy and transportation infrastructure expansion solutions, and assesses the long-term impacts of the resulting portfolios in terms of cost and emissions. There have been many studies that have looked into optimizing the siting of biomass processing plants (for bio-power and biofuels) in a smaller geographical regions for some future year [12,13], considering the feedstock production locations, impact on local transportation, and finally drawing conclusions on the bio-renewables economics. However, fewer models and methodologies are able to plan bio-renewable infrastructures considering their long-term roles in both energy and transportation sectors, and assess their impacts at the national scale. A national scale study performed by the researchers at the RAND corporation estimated about 37% of the U.S. national energy coming from biomass for realizing 25% renewable portfolio standard (RPS) mandate by the year 2025 [14]. The National Renewable Energy Laboratory (NREL) envisions biomass to provide at best about 15.2% of national generation in the year 2050 under a 80% renewable energy scenario [15]. Given that the above two are electric-only planning studies, the Energy Information Administration (EIA) provides forecasts based on the National Energy Modeling System (NEMS), which simulates energy and transportation sector operations for a given future portfolio. The 2014 issue of Annual Energy Outlook (AEO), released by EIA, forecasts increasing penetration of bio-renewables by the year 2040, especially 27% of the renewable energy coming from bio-power [16]. In comparison to NEMS, which is an equilibrium model that cost-effectively balances supply-demand separately within each sector, this paper provides planning perspectives from a multi-sector integrated optimization model.

This paper presents a planning model that integrates biomass pathways into a 40-year multi-period optimization model called NETPLAN, which co-optimizes the investments and operations in interdependent energy and transportation infrastructure systems [17,18]. The presented model helps to find the most promising