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Global zero emissions scenarios: The role of biomass energy with carbon capture and storage by forested land use

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HIGHLIGHTS

- Three zero-emission scenarios are investigated for achieving ⩽2 °C warming targets.
- A model for energy, materials, and biomass with a simplified climate model is used.
- The 2 °C target appears attainable with significant forested land use.
- BECCS contributes to meeting zero-emission targets and to energy supply.

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ABSTRACT

We investigate the prospects of three zero-emission scenarios for achieving the target of limiting global mean temperature rise to 2 °C or below, and compare them with the business-as-usual (BAU) scenario involving no climate policy intervention. The "2100 zero" emissions scenario requires zero emissions after 2100 until 2150. The "350 ppm zero" emissions scenario entails zero emissions in the latter half of this century, which can be achieved by the cumulative emissions constraints of the Wigley–Richels–Edmonds (WRE) 350 from 2010 to 2150. Finally, the "net zero" scenario requires zero cumulative emissions from 2010 to 2150, allowing positive emissions over the coming several decades that would be balanced-out by negative emissions in the latter half of the century. The role of biomass energy carbon capture and storage (BECCS) with forested land is also assessed with these scenarios. The results indicate that the 2 °C target can be achieved in the "net zero" scenario, while the "350 ppm zero" scenario would result in a temperature rise of 2.4 °C. The "2100 zero" scenario achieved a 4.1 °C increase, while the BAU reached about 5.2 °C. BECCS contributed to achieving zero-emission requirements while providing a limited contribution to energy supply. The findings indicate substantial future challenges for the management of forested land.

1. Introduction

1.1. Background

Many studies have been conducted on the goal of limiting global mean temperature rise to 2 °C [1–5] or less [6–13] compared with baseline pre-industrial levels; however, this goal is so challenging to meet that relatively few modeling studies have been produced. Thus, the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC-AR5) [14] did not include in its database, studies that targeted a temperature increase of less than 2 °C. Modeling studies are needed to assess the probability of attaining such stringent goals and to identify how they might be achieved. Meeting these stringent targets will depend on the use of bioenergy with carbon capture and storage (BECCS) [7,15–17]. BECCS is a technology for sequestering carbon dioxide (CO_2) from the atmosphere, via the biosphere, into geological layers. One of the key requirements of BECCS is land for biomass production, with 200 Exa Joule (EJ) per year (EJ/yr) of bioenergy estimated to require approximately 500 Mha of land, corresponding to one-third of global crop land [7].

However, very few reports have investigated the land requirements of this technology [6]. Moreover, although existing studies of "2 °C or less" utilized forecasting trajectories such as greenhouse gas (GHG) emissions, global temperature rise, intensities of energy and carbon, shadow price of carbon, and primary energy supply,

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they had not presented the possible share of BECCS in the final energy sectors. Studies on BECCS [7,15,16] were conducted under stringent CO_2 concentration targets or radiative forcing targets to comply with the IPCC reports, and then addressed temperature targets. However, very few studies (whether within this journal or the wider literature [18–21]) have addressed zero-emission targets at a global level, despite the many articles published on various emission reduction levels at a national scale [22–26].

1.2. Research objectives

In this study, we focus on the role of BECCS in terms of forested land use and global energy systems, using three alternative zero-emission scenarios from the Special Report on Emissions Scenarios (SRES) A1T [27], to address the climate policy targets for global mean temperature rise. We believe that the novelty and significance of our study is as follows: Compared with existing studies, the first consideration is to highlight the technological feasibility of BECCS, especially to assess its role in the final energy sectors, which has received little attention in previous studies [28]. Secondly, we investigate the land requirements of BECCS, which has only been examined in a small number of studies [6]. Thirdly, we evaluate various zero-emission scenarios with global mean temperature rise to understand these features of BECCS under various climate policies. Furthermore, in terms of the originality of our study: although many previous articles in this journal focus on emission reductions at a national or regional level through the use of technological countermeasures, very few have addressed zero-emissions on a global scale. Since we focus on these features, the socio-economic aspects of BECCS (e.g., system cost increase, shadow price of carbon, and strategic roadmaps) are left for future publications, since the results and discussion of such topics are too wide-ranging for inclusion in a single paper.

The structure of this article is as follows: Section 2 describes our model and climate policy scenarios; Sections 3 and 4 present the results and discussion, respectively, on CO_2 balance and climate change, land use, and energy supply structure; Section 5 concludes this work.

2. Methodology

2.1. Outline of model

Our global model consists of three hard-linked models (Fig. 1) for the following resources with a simplified climate model: 1. Energy, comprising: fossil fuels (coal, oil, and gas); uranium; and renewables, including: biomass and geothermal (heat and power), solar (photovoltaics, or PV), heat (concentrated solar power, or CSP), space (space solar power system, or SSPS), ocean (waves, tidal, temperature difference), hydropower (small-, medium-, and large-scale), and wind (on- and offshore); 2. Minerals (iron ore, bauxite, copper, zinc, lead, and limestone); 3. Biomass (logs, wood pulp, and timber); and 4. Food, comprising: meat (pork and chicken, lamb and beef) and cereals (rice, wheat, and corn). The models provide a consistent structure for supplying the resources to meet exogenous demand scenarios.[1] The left side of Fig. 1 indicates resource supply, while the right side shows demand together with end-use products and waste disposal. The upper section illustrates the mineral and material flows, the lower section shows biomass and food flows, and the middle section shows energy flows. These three sections correspond to the three resource models for the balance of materials, biomass, and food via land use and energy systems, respectively.

The blue, red, green, and orange lines indicate flows to meet the demands for electricity, heat, and transportation via hydrogen and liquid fuel, respectively, while the solid and dotted lines indicate flows of energy products and their resources, respectively. The black lines show material flows, with solid lines representing arterial industry; both dashed and dot-dashed lines represent venous industry, and indicate biomass residues and scrap materials respectively.

Electricity and heat consumed in the materials balance model are also endogenously linked to those in the energy systems model. Fly-ash from pulverized-coal-fired power plants in the energy systems model is endogenously linked to the Portland fly-ash cement process in the materials balance model. In addition to wood and logs used as fuel for BECCS, biomass residues from various biomass and food processes and products are used as a potential resource supply in the energy systems model.

The model shown in Fig. 1 includes the dominant CO_2 emitters, based on level of production and consumption of energy and materials. Emissions from fossil fuel consumption and deforestation, and those containing non-CO_2 greenhouse gases (NCGHG), are included in this model. Various options for CO_2 storage and sequestration by afforestation via land-use change are also considered. Equations and data setting for the simplified climate model were adopted from the RICE 2010 model [29].

2.2. The objective function

Our modeling approach is based on perfect foresight, assuming that costs and expansion rates of technologies[2] are known and can be taken into account via linear programing optimization. This idealized approach provides consistent, economically efficient future scenarios of technology deployment and resource allocation to meet the climate target.

Our global model includes 10 regional areas or groups[3] (*rg*) with time horizons between 2010 and 2150 at 10-year intervals[4] (*yr*).

[1] Energy (electricity, heat, and transportation), materials (electricity, machinery, transportation, construction, and civic infrastructure), food (pork and chicken, lamb and beef, and cereals), and wood (lumber and boards, paper, and fuel).

[2] Technology options included 28 types of power (8 types of fossil fuel (coal, integrated gasification combined cycle (IGCC), oil, and gas, without and with CO_2 capture), 4 types of biomass (co-firing and integrated gasification (IBGCC), without and with CO_2 capture), hydrogen, 5 types of nuclear energy (light water reactor (LWR), fast breeder reactor (FBR), 3 types of nuclear fusion), and 10 types of renewables (PV, CSP, SPSS, onshore wind, offshore wind, conventional hydropower and pump, small- and medium-scale hydropower, geothermal power, ocean wave and tidal power, and ocean thermal energy conversion (OTEC)); 15 types of liquids, including refined oil, ethanol (bioethanol by biomass residue fermentation, without and with CO_2 capture), methanol (coal, gas, and biomass residue), biodiesel, and FT synfuel (biomass liquefaction, coal, natural gas, and heat utilization of nuclear fusion for biomass residue, without and with CO_2 capture); 12 types of hydrogen production, including fossil (coal, oil, and gas, without and with CO_2 capture), biomass (gasification, without and with CO_2 capture), nuclear (high-temperature gas cooling reactor (HTGR) and heat utilization of nuclear fusion for biomass residue, without and with CO_2 capture), and renewable (electrolysis by large deployment of PV); 8 types of heat, including biomass (biomass pellet heating, biomass heating with CHP (combined heat and power), biomass anaerobic digestion with CHP, and municipal solid waste with CHP), geothermal (conventional deep geothermal with CHP, advanced deep geothermal with CHP, and shallow geothermal heating and cooling), and solar; 11 types of transportation, including passenger car (internal combustion engine (ICE), plug-in hybrid electric vehicle (PHEV), electric vehicle (EV), and fuel cell vehicles (FCV)), bus (ICE and FCV), truck (ICE and FCV), aviation, marine, and rail; 8 types of steel production, including blast furnace with converter and electric furnace with directly reduced iron (DRI) for construction steel and mechanical machinery steel, with and without CO_2 capture; 5 types of non-ferrous metals production, including aluminum, copper (dry and leached), lead, and zinc; 4 types of cement kilns, including wet, dry, advanced dry, and advanced dry with CO_2 capture; and 3 types of cement mills, including Portland cement, blast furnace cement, and Portland fly-ash cement.

[3] North America, Western Europe, Japan, Oceania, China, Southeast Asia (including member countries of the Association of Southeast Asian Nations (ASEAN) and India), the Middle East and North Africa, Sub-Saharan Africa, Latin America, and the former Soviet Union and Eastern Europe.

[4] 2010, 2020, ..., 2150.

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