nature climate change

LETTERS

PUBLISHED ONLINE: 9 FEBRUARY 2015 | DOI: 10.1038/NCLIMATE2488

Biomass enables the transition to a carbon-negative power system across western North America

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Sustainable biomass can play a transformative role in the transition to a decarbonized economy, with potential applications in electricity, heat, chemicals and transportation fuels[1–3]. Deploying bioenergy with carbon capture and sequestration (BECCS) results in a net reduction in atmospheric carbon. BECCS may be one of the few cost-effective carbon-negative opportunities available should anthropogenic climate change be worse than anticipated or emissions reductions in other sectors prove particularly difficult[4,5]. Previous work, primarily using integrated assessment models, has identified the critical role of BECCS in long-term (pre- or post-2100 time frames) climate change mitigation, but has not investigated the role of BECCS in power systems in detail, or in aggressive time frames[6,7], even though commercial-scale facilities are starting to be deployed in the transportation sector[8]. Here, we explore the economic and deployment implications for BECCS in the electricity system of western North America under aggressive (pre-2050) time frames and carbon emissions limitations, with rich technology representation and physical constraints. We show that BECCS, combined with aggressive renewable deployment and fossil-fuel emission reductions, can enable a carbon-negative power system in western North America by 2050 with up to 145% emissions reduction from 1990 levels. In most scenarios, the offsets produced by BECCS are found to be more valuable to the power system than the electricity it provides. Advanced biomass power generation employs similar system design to advanced coal technology, enabling a transition strategy to low-carbon energy.

An assessment of BECCS deployment as part of a suite of low-carbon technologies is a critical research need[9]. Such an analysis requires detailed spatial and temporal assessment of distributed biomass supply, electricity demand, deployment of intermittent renewables, and electricity dispatch capabilities. We employ the SWITCH optimization model for long-term strategic planning of the electric system[10,11]. SWITCH leverages a unique combination of spatial and temporal detail to design realistic power systems that meet policy goals and carbon emission reduction targets at minimal cost[12]. The version of the SWITCH model used here encompasses the region of the Western Electricity Coordinating Council (WECC), which includes the western United States, two Canadian provinces and a small portion of Mexico. WECC contains high-quality wind and solar resources, but relatively limited bioenergy resources: the eastern United States, for example, has a larger absolute bioenergy resource[13]. Existing studies of low-carbon transitions in western North America have generally reserved biomass for biofuels production, rather than for electricity[10,14].

Western North America contains biomass resources from forestry, wastes, agricultural residues and dedicated energy crops, although supply is limited by land and sustainability practices (Fig. 1)[13]. In total, we identify 1.9×10^9 MMBtu (2,000 PJ) of economically recoverable bioenergy available annually from solid biomass by the year 2030, sufficient for ~7–9% of modelled demand for electricity in 2050. Our estimates for availability in California are smaller than other studies, which tend to focus on 'technical potential' rather than 'economically recoverable' resources[14,15]. Although barriers to biomass recovery exist even for economically recoverable resources, we choose these resources as a reasonable approximation of biomass potential. We model solid biomass fuel costs as a piecewise linear supply curve disaggregated by 50 regions across western North America. Biomass supply from dedicated energy crops represents only 7% of the total supply, so direct land use impacts from the biomass feedstocks used in this study would be minimal. Dedicated feedstocks, such as switchgrass and pulpwood, tend to have higher prices than wastes and residues.

The implications of BECCS for the economics and carbon emissions of regional power systems to 2050 have not been previously investigated in detail. To address this gap, we explore scenarios for the electricity sector that are consistent with economy-wide decarbonization, but vary the allocation of biomass across sectors of the economy (Supplementary Table 5). We explore scenarios with WECC-wide power sector CO_2 emissions reductions from 1990 levels by 2050 ranging from 105% to 145%, which previous work has found would be consistent with economy-wide goals should biomass be used for electricity[16]. To understand biomass deployment in carbon-neutral and carbon-negative power systems, we mandate a 105% reduction (−105%), 120% reduction (−120%) and 145% reduction (−145%) in CO_2 emissions by 2050. These scenarios require aggressive research and development on CCS and BECCS over the coming decades. Our case without biopower mandates an 86% reduction in CO_2 emissions from 1990 levels by 2050 (−86% No Biomass). We vary this scenario by disallowing CCS technologies (−86% No CCS No Biomass) and allowing biomass (−86%). We continue operation of some existing nuclear plants, but do not allow new nuclear power. We do not conduct a complete economy-wide assessment of CO_2 emissions across WECC or optimal biomass allocation among sectors.

Without biomass technologies (−86% No Biomass), the resource mix is reliant on other renewable energy technologies including

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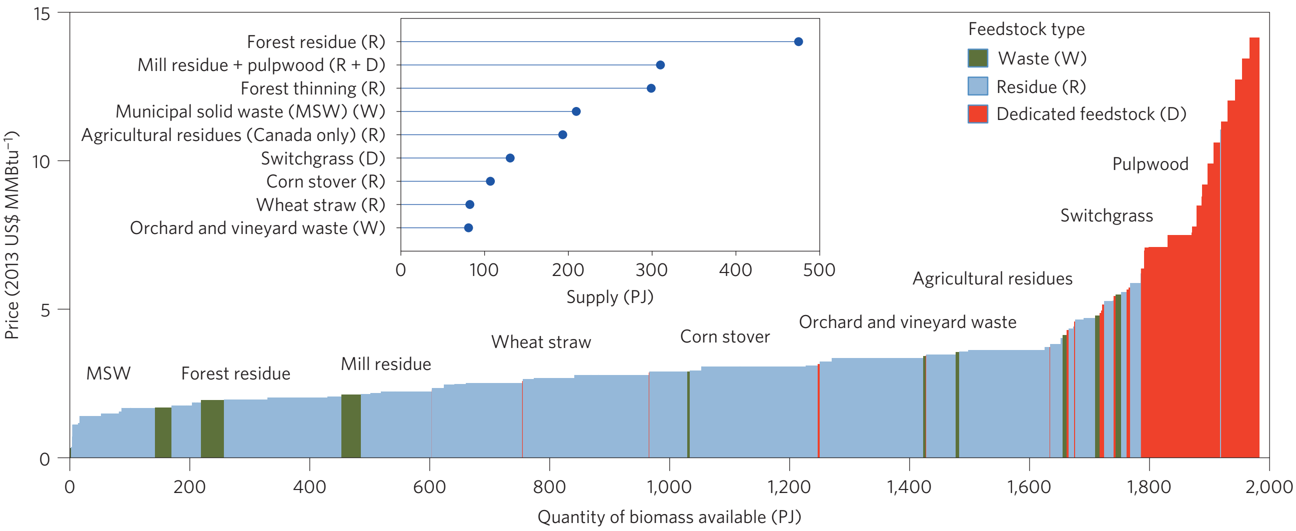

Figure 1 | Supply curve of available solid biomass post-2030. Biomass can provide up to 2,000 PJ yr^{-1} of energy in 2030 for the electricity system, from a number of waste and dedicated sources. Labels on the supply curve represent the principal price region of a given biomass source. Feedstocks are classified as wastes (W), residues (R) or dedicated feedstocks (D). Dedicated feedstocks tend to be the most expensive.

wind, solar, hydro and geothermal for 86% of total electricity generated in 2050 (Fig. 2a). Low-carbon power systems employ gas technologies (with and without CCS), storage and transmission to compensate for renewable intermittency. Coal (with and without CCS) plays little to no role in energy generation because of its relatively high level of CO_2 emissions (Fig. 2b). CCS technology reduces CO_2 emissions from coal, but coal CCS still has higher emissions than gas CCS (Supplementary Table 3). Without CCS technologies (−86% No CCS No Biomass), the resource mix is even more reliant on renewable energy, up to 94% in 2050.

Biomass CCS technologies enable a power system more reliant on baseload and fossil-fuel technologies in 2050 at moderate power sector emission caps (between −86% and −105%). In the −86% case, coal CCS, biomass cofiring and BECCS cumulatively provide 20% of electricity generated, enabling lower-cost gas resources to generate 22% of electricity while still meeting CO_2 emission constraints. In 2050, 43 GW of coal and biomass technologies are installed throughout western North America (Supplementary Fig. 5a). Owing to the dispersed nature of the fuel resource, biomass deployment is distributed across the WECC. In the context of the electric power sector, if the cap on carbon emissions is held constant, the introduction of bioenergy for BECCS reduces power system costs, carbon abatement costs and the need for electrical energy storage for intermittent renewable energy (Fig. 2a and Supplementary Text).

As the carbon cap becomes more stringent between the −105% and −145% case, we see CO_2 emissions from combined-cycle gas turbine (CCGT) technology shrink before being captured by CCS, as well as increased renewable generation from wind and solar (Fig. 2a,b). Coal CCS and biomass cofiring CCS play a significant role in the −105% case (~13% of average 2050 electricity generated), a smaller role in the −120% case (2%), and no role (0%) in the resource mix under the −145% case (Supplementary Fig. 5b). This reduction in coal CCS and biomass cofiring CCS is explained by the increasing severity of the CO_2 emissions constraint. Gas turbines are installed across all scenarios to provide flexibility, dispatchability and system reserves.

Our −145% scenario demonstrates a power system that generates almost all electricity from renewable resources, representing how the power sector might be configured if climate change is severe, or emission reductions in non-electricity sectors are more expensive than the electricity sector. In our −145% case, biomass CCS plants provide carbon-negative baseload power in 2050, resulting in overall emissions of −135 $MtCO_2$ yr^{-1} in the WECC (Fig. 2a,b). Generation, electricity costs (Fig. 2a) and dispatch (Fig. 3 and Supplementary Fig. 9) are similar between the −86% No Biomass and −145% cases, with the exception of BECCS technology deployment. Low-carbon scenarios without BECCS and carbon-negative scenarios with BECCS ultimately result in qualitatively similar deployment of gas and renewable generation.

In all cases where biomass is allowed, the power system employs between 90 and 98% of all biomass supply available in 2050, regardless of the extent of CO_2 reduction or availability of low-carbon flexible assets. This indicates that biomass systems are cost-effective in the context of low-carbon power systems in western North America, especially owing to negative CO_2 emissions from BECCS. Given the very small amount of net CO_2-emitting infrastructure in the −145% case, we do not expect that that emissions could fall well below a 145% reduction with projected levels of biomass availability. Although technology cost, life-cycle CO_2 emissions and performance assumptions in carbon-negative power systems alter the relative deployment of coal CCS and intermittent renewables, they have little effect on biomass deployment (Supplementary Information).

We find that the value of BECCS lies primarily in the sequestration of carbon from biomass, rather than electricity production. This result reconfirms previous results found using integrated assessment models[17]. To illustrate this point, we explore cases in which BECCS plants capture CO_2 emissions but do not produce electricity. The average cost of electricity when BECCS is used exclusively for carbon sequestration is only slightly higher (~6%) than when BECCS provides both sequestration and electricity (Supplementary Fig. 6). Carbon sequestration from biomass, regardless of the technology employed or capital cost, could be a key driver of climate change mitigation pathways in the 2050 time frame.

Our analysis has several implications for CO_2 reduction, technology development and biomass allocation. Negative emissions from BECCS can offset CO_2 emissions from fossil-fuel energy across the economy. The amount of biomass resource available limits the level of fossil-fuel CO_2 emissions that can still satisfy carbon emissions caps. Efforts to expand biomass supply can increase demand for water, land and fertilizer, or other ecosystem impacts[18,19]. Given the level of projected biomass availability in WECC, it would seem that there is little room for coal CCS

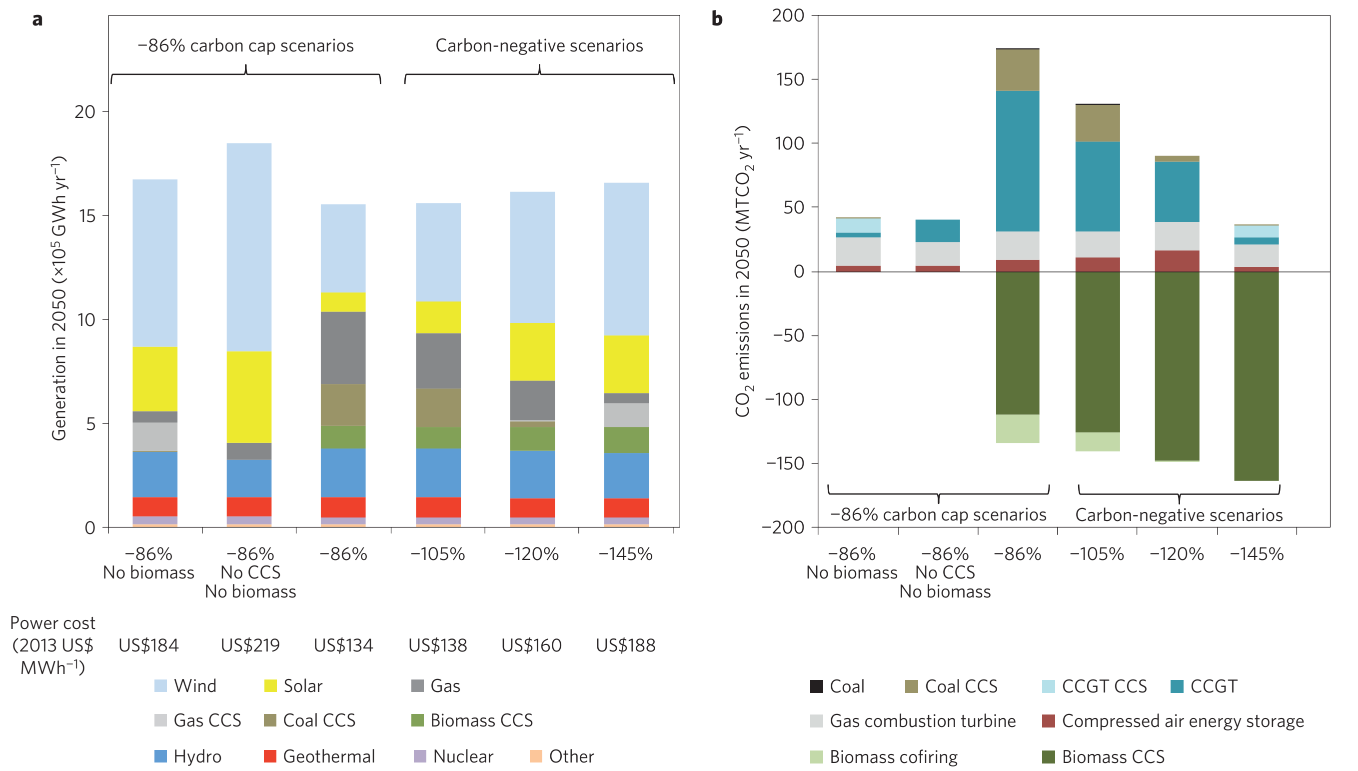

Figure 2 | Generation, power cost and carbon emissions in 2050. a, Fossil-fuel use is phased out as the power system becomes carbon-negative, transitioning from coal CCS and gas, to gas combined with CCS. 'Other' includes generation from coal and non-CCS bioenergy inputs. Total generation exceeds system load because of transmission, distribution and storage losses as well as curtailment of generation on resources. **b**, Biomass CCS and biomass cofiring CCS on coal CCS plants provide negative CO_2 emissions. As emissions limits are reduced, fossil-fuel CO_2 emissions shift from coal and CCGT to CCGT with CCS. BECCS can sequester ∼165 $MtCO_2$ yr^{-1}.

technology to play a role in an energy system consistent with economy-wide emissions reductions goals. Gas CCS, however, can contribute moderately to economy-wide decarbonization owing to its operational flexibility (Supplementary Fig. 5).

Our analysis suggests that installation of up to 10 GW of BECCS capacity between 2030 and 2040, with additional capacity additions thereafter, could be a key part of meeting stringent climate goals in the WECC. Such a goal would require a concentrated effort in finance, site selection, biomass sourcing, geological characterization, permitting, site-specific environmental impact assessments and community consultation. Biomass harvesting, drying and transportation present logistical challenges to rapid deployment. However, we find necessary capacity deployment rates for BECCS to be smaller than those for other intermittent renewables or gas.

Advanced biomass power generation technology employs similar system design to advanced coal technology, including CCS and integrated gasification combined-cycle (IGCC) systems[20]. Such systems boast higher efficiency and more easily capture CO_2 emissions than conventional steam turbines; these characteristics become even more desirable in light of biomass's lower energy density, higher feedstock cost and distributed geographic nature. Research needs include systems integration and technology advancement in gasification, air separation, gas cleaning, shift catalysis, and gas turbines that operate on H_2-rich syngas[2,21]. Moving forward, the fossil-fuel industry could embrace higher and more efficient levels of biomass utilization combined with CCS technology development as a transition strategy to low-carbon energy. BECCS could enable some of the world's largest carbon-emitting entities to instead become some of the world's largest carbon-sequestering entities.

Biomass could enable CO_2 reduction not only in the electricity sector, but also in the transportation and industrial sectors for fuels, heat and chemicals. We estimate that cellulosic biofuel production from available biomass in WECC can reduce emissions by 75 $MtCO_2$ yr^{-1} by displacing gasoline, based on literature conversion efficiency and near-term carbon intensity values[22]. In contrast, if biomass is made available to the power sector, BECCS can sequester 165 $MtCO_2$ yr^{-1} and also displace fossil-fuel electricity. At the conversion efficiencies assumed in this study, bioelectricity contains 28–45% of the net energy of candidate cellulosic ethanol conversion pathways, but can provide as much as 41% more transportation miles because of the high efficiency of battery electric drive vehicles (Supplementary Table 6)[22,23].

Our analysis indicates that despite its value to the power sector, carbon sequestration from biomass may be more cost-effective in other sectors. We find BECCS technology deployment at abatement costs as low as US$74 per tCO_2 in the −86% case, with more stringent emission caps incurring higher abatement costs. Such costs are slightly higher than afforestation schemes (∼US$5–40 tCO_2^{-1}), biochar projects in North America (US$30–40 tCO_2^{-1}), and cellulosic biofuel production (US$35 tCO_2^{-1}), but are far lower than projected abatement costs for direct air capture of CO_2, which has been assessed as high as US$1,000 per tCO_2 (refs 24–27). Should carbon sequestration be more effective by means of alternative abatement methods, the electric power sector would find it economical to purchase those offsets. A roadmap of economy-wide biomass policy focused on CO_2 reduction should account for both the technical potential and economic costs of biomass deployment across sectors. Increasing efficiency, reducing costs, and commercializing carbon-negative biomass technologies could make such a roadmap possible.

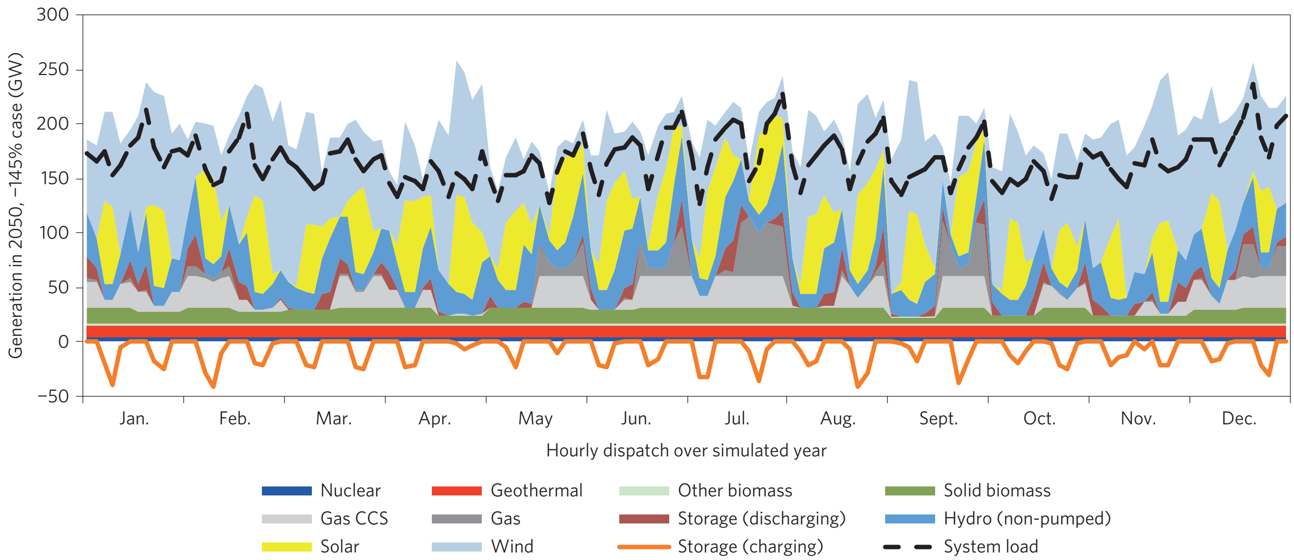

Figure 3 | Hourly dispatch in 2050 in the −145% case. Power system dispatch is shown in sampled hours from two days (peak and median day) each month between January–December. With the exception of BECCS, dispatch is similar between the −86% No Biomass and −145% case (Supplementary Fig. 9). Low-carbon scenarios without BECCS and carbon-negative scenarios with BECCS ultimately result in similar deployment of gas and renewable generation. 'Other Biomass' includes both liquid and gaseous biomass supplies.

Methods

Model description and additional methods are presented in detail in the Supplementary Information.

Biomass technologies. SWITCH inputs include technology cost profiles, construction time frames, outage rates, generation flexibility, retrofit ability and heat rates for a broad range of existing and new conventional and renewable energy generation technologies. Technical performance metrics and evolution of capital and operations and maintenance costs are drawn primarily from Black and Veatch[28]. We assume that future biomass plants will use IGCC technology, whereas existing plants use steam turbines (Supplementary Tables 1 and 2). CCS technologies are modelled with a default capture efficiency of 85%, and are available for installation on biomass IGCC, coal and natural gas technologies after 2025. We do not explicitly model criteria pollutants, which may require additional control technology to be installed on coal and biopower technologies.

Black and Veatch estimates capital and operating costs for biomass IGCC plants, but its data set does not include similar values for BECCS plants. As assumptions between cost data sets can differ substantially, we choose to estimate cost and efficiency parameters for BECCS plants from other similar plant types. We derive the capital cost of CCS equipment, the efficiency penalty of performing CCS, and the increase in non-fuel variable operations and maintenance costs for BECCS from coal IGCC and coal IGCC–CCS systems. Our BECCS capital cost estimates are within 5% of those by the National Energy Technology Laboratory for biomass IGCC–CCS facilities[29]. Increasing the capital cost of BECCS would probably not lower deployment owing to the high value of carbon sequestration. As a large amount of the biomass resource is already deployed in our scenarios, lowering the capital cost would also be unlikely to affect deployment.

Biomass supply. Fuel costs for solid biomass are input into the SWITCH model as a piecewise linear supply curve for each load area. This piecewise linear supply curve is adjusted to include producer surplus from the solid biomass cost supply curve to represent market equilibrium of biomass prices in the electric power sector. As no single data source is exhaustive in the types of biomass considered, solid biomass feedstock recovery costs and corresponding energy availability at each cost level originate from a variety of sources (Supplementary Table 4). We consider two scenarios for biomass life-cycle assessment: carbon neutrality, as feedstocks are primarily wastes or low-input crops grown on marginal lands; and a sensitivity scenario with solid biomass penalized at 10% of its biogenic carbon content. In the carbon-neutral cases, we assume that direct emissions from harvesting and transport—a small source of emissions—will be minimized as the entire economy is decarbonized[30]. The sensitivity case represents increased emissions such as those from transportation, fertilizer, or soil organic carbon from residue collection, which recent empirical work suggests may be larger than previously thought[31].

Biomass cofiring and modelled scenarios. Cofiring is allowed up to 15% of total output from a single coal plant. When cofiring is installed on a plant with CCS technology, we assume that the heat rate increases by the same percentage when sequestering carbon as does coal IGCC relative to coal IGCC–CCS.

CCS reservoirs and transportation. Large-scale deployment of CCS pipelines would require pipeline networks from CO_2 sources to CO_2 sinks. We require CCS generators that are not near a CO_2 sink to build longer pipelines, thereby incurring extra capital cost. If a load area does not does not contain an adequate CO_2 sink within its boundaries, a pipeline between the largest electrical substation in that load area and the nearest CO_2 sink is built. We derive pipeline costs from existing literature. CCS plants must send all of their CO_2 output to their closest reservoir.

Scenario development. All scenarios enforce a carbon cap and existing Renewable Portfolio Standard laws. We disallow new nuclear generation. Electricity demand profiles include extensive energy efficiency, electric heating, and electric vehicle penetration consistent with economy-wide decarbonization. We sample hourly demand for each of 50 areas within WECC for six hours of each of 12 representative days in the decades 2020–2050. Investment decisions are made in four periods between 2016 and 2055; these periods are 2016–2025 ('2020'), 2026–2035 ('2030'), 2036–2045 ('2040') and 2046–2055 ('2050'). In each modelled hour, demand must be met by the optimization, as well as capacity and operational reserve margin constraints to ensure system reliability.

Received 3 August 2014; accepted 3 December 2014; published online 9 February 2015

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Acknowledgements

We thank the California Energy Commission for support. This paper reflects the views of the authors and does not necessarily reflect the view of the California Energy Commission or the State of California. We thank the Class of 1935 of the University of California, Berkeley, the Karsten Family Foundation, the Zaffaroni Family (to D.M.K.), and the Link Foundation (to J.H.N.). This material is based on work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE 1106400 (to D.L.S.).

Author contributions

D.L.S., J.H.N., J.J. and A.M. designed research and analysed data; D.L.S. implemented biomass cofiring retrofits and drafted the paper; J.H.N. built the biomass supply curve; D.L.S., J.H.N., J.J., A.M. and D.M.K. revised the paper; D.M.K. supported development of the modelling platform and directs the research group.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.M.K.

Competing financial interests

The authors declare no competing financial interests.