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Energimyndighetens titel på projektet – svenska Systemanalys av biomassa och koldioxidavskiljning över energisektorerna	
Energimyndighetens titel på projektet – engelska Systems analysis of biomass and carbon capture across energy sectors	
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Förord

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Sammanfattning

Europeiska ansträngningar att uppnå netto-negativa utsläpp kan bli avsevärt dyrare utan biomassa i energimixen. Resultaten visar att uteslutning av biomassa från Europas framtida energisystem skulle öka de totala systemkostnaderna med ~20%, ungefär motsvarande regionens nuvarande försvarsutgifter. I IPCC-scenarier ses biomassa ofta tillsammans med koldioxidavskiljning och lagring (CCS). Osäkerheter kring biomassatillgång påverkar dock potentialen för negativa utsläpp, och möjligheter till CCUS påverkar kostnadseffektiva strategier för biomassaanvändning. I detta projekt analyserades hur biomassa i kombination

med CCUS förändrar resurs- och kostnadseffektiv biomassaanvändning för att uppnå klimatmålen i energisystemet (el, värme, transport och industri), under vilka förhållanden det infångade kolet används istället för att lagras, vilka osäkerheter som påverkar dessa aspekter och hur detta i sin tur kan påverka energisystemet som helhet.

Biomassa är en mångsidig men begränsad förnybar resurs, och användningen behöver prioriteras. Medan biomassa spelar en viktig roll mot fossilfrihet, kan dess mest värdefulla bidrag vara som en källa till förnybart kol som kan fångas och antingen lagras under jord eller användas för att producera syntetiska bränslen.

En liten mängd biomassa-driven elproduktion - cirka 1% av den totala produktionen - skulle hjälpa till att upprätthålla elförsörjningens tillförlitlighet i ett system dominerat av vind- och solkraft. Utöver denna nischroll kan biomassa dock användas flexibelt över olika sektorer utan att påverka kostnaderna avsevärt. Det spelar mindre roll om biomassa används för kraftvärme, drivmedelsproduktion eller industriell processvärme, om dess kolinnehåll utnyttjas effektivt genom koldioxidavskiljningstekniker.

Att helt ta bort biomassa skulle dock kräva en betydligt större och mer utmanande expansion av förnybar el, elektrolysörer och direct air capture. Detta skulle öka kostnaderna för det Europeiska energisystemet med \textasciitilde20%, eller 169 miljarder euro årligen.

Medan oro över biomassans hållbarhet har lett till strängare restriktioner i EU-politiken, pekar studien på att uteslutning av biomassa skulle göra klimatmålen avsevärt dyrare och mer utmanande att uppnå.

Summary

European efforts to achieve net-negative emissions could become significantly more expensive without biomass in the energy mix. Results suggest that excluding biomass from Europe's future energy system would increase total system costs by ~20% - roughly equivalent to the region's current defence spending.

Biomass is often seen jointly with carbon capture in influential studies and IPCC publications. However, uncertainties regarding biomass availability affect the potential of negative emissions and carbon storage or usage availability affects cost-effective biomass usage strategies. We bridge a gap in the academic research on biomass usage and carbon capture, by assessing biomass usage in a state-of-the-art sector-integrated energy systems model with a high spatio-temporal resolution. We assess how biomass in combination with CCUS changes the resource- and cost-efficient use of biomass to achieve climate targets across all

energy systems (electricity, heat, transport, industry), under which conditions the captured carbon is used instead of stored, how various uncertainties affect these aspects and how this in turn may affect the energy system as a whole.

Biomass is a versatile but limited renewable resource, and usage needs prioritisation. While biomass plays a vital role in decarbonisation efforts, its most valuable contribution may not be as an energy source per se, but rather as a source of renewable carbon that can be captured and either stored underground or used to produce synthetic fuels.

A small amount of biomass-powered electricity generation - around 1% of total generation - would help maintain grid reliability in a system dominated by wind and solar power. Beyond this niche role, however, biomass could be deployed flexibly across different sectors without significantly impacting costs. It matters less whether biomass is used for combined heat and power, liquid fuel production or industrial process heat, if its carbon content is utilized effectively through carbon capture technologies.

Yet completely eliminating biomass would require a substantially larger and potentially more challenging expansion of renewable electricity, electrolysers, and direct air capture facilities. The study finds that this drives up system costs by ~20%, or €169 billion annually.

The findings highlight the delicate balance policymakers must strike. While concerns about biomass sustainability have led to tighter restrictions in EU policy, the study finds that excluding biomass entirely makes climate targets significantly more challenging and expensive to achieve.

Inledning/Bakgrund

Biomass can be used for many applications within the energy system, such as heat and biofuels, and can serve as a renewable dispatchable power reserve. Combined with CCS it can enable negative emissions which can offset difficult to reduce emissions from e.g. agriculture [1]. However, the sustainable biomass potential is limited and uncertain, and the potential of carbon capture and storage is uncertain and unproven. While there is potential for cost-effective negative emissions with BECCS, the reliance on both biomass [2–4] and carbon capture [5–7] for achieving climate targets is coupled with risks and sustainability concerns, dividing both the academic community and the public debate.

Biofuels may be needed to achieve sectoral renewable targets in transport, especially in e.g. aviation where other alternatives are scarce. This would however reduce the potential for BECCS, which is higher in stationary applications such as combined heat and power plants. Also, there may be benefits to using the captured carbon as a resource for producing electrofuels or chemicals for sectors where electrification is not a viable option [8–10].

Global climate and energy integrated assessment models (IAMs) often include bioelectricity and biofuel production coupled with CCS [11, 12]. If either biomass or CCS is excluded, results differ substantially, often with ambitious climate targets out of reach [13–15]. Recent analyses indicate a higher potential deployment of variable renewables (solar photovoltaics and wind power) and the possibility to achieve ambitious climate targets with less negative emission technologies [16–18].

Also, the potential role of Direct Air CCS (DACCS) has recently been highlighted, which is coupled with a large cost uncertainty but also a high potential [19–22]. The uncertainty and divided discourse on both bioenergy and CCS has led to a rather polarised academic discussion on BECCS. While in many studies it is required to achieve climate targets [11], others exclude CCS altogether [23–25], some include bioenergy but instead of BECCS use DACCS [26] and some exclude both bioenergy and CCS [27, 28]. There is also criticism regarding the realism and real-world achievability of energy system optimisation modelling results [29, 30]. Taking current infrastructure, existing and planned point-sources and other constraints into account is important to assess biomass usage at least for the medium term and can be contrasted to biomass usage in less constrained long-term energy system futures.

Although a broad range of biomass and CCS scenarios have been assessed in global models [14], the range of possible outcomes and the sensitivity to different parameters regarding biomass and CCS has not been analysed with a high spatio-temporal resolution. This is important, as biomass and carbon capture are often co-dependent, but also depend on the deployment of variable renewables, which are better depicted using a high spatio-temporal resolution. Spatial details are also important to capture transmission, as well as transport of biomass and captured CO_2.

Analyses with high spatio-temporal detail which include competing usages of biomass, DACCS and the usage of captured carbon as a feedstock in industry or for fuel production (carbon capture and utilization, CCU) are lacking. Often, the usage of carbon has been assessed in a binary fashion, with the option of CCS either available or not [8, 10]. Carbon storage is controlled by a few actors and the scaling up of new technologies such as CCS may prove to be challenging [31], which may drive up prices and affects biomass and carbon usage and negative emission strategies. More detailed analyses of factors and determinants and their uncertainty is thus required.

The knowledge on BECCUS is increasing, with several projects ongoing or planned. Diverse strategies are pursued regarding usage of the captured carbon, with closeness to ports being an important factor. BECCS initiatives in Sweden include CinfraCap [32], Stockholm Exergi [33], Cementa [34] and Stora Enso [35]. Commercial carbon storage sites in Norway are emerging, with an agreement with Swedish companies [36]. There are several BECCU initiatives focusing on electrofuels [37–41] and chemicals [42]. The increasing knowledge base can be used to improve data, increase the detail in the modelling, and to highlight uncertainties which are yet to be overcome.

The purpose of this project is thus to highlight the effect of uncertainties regarding biomass and carbon capture on long-term strategies for biomass usage. The effect of different biomass availability and industry and energy system scenarios will be assessed and combined with up-to-date knowledge from concrete CCUS initiatives and from companies with a CCUS strategy, and through analyses in a state-of-the-art sector-integrated European energy system model.

Biomass is a key part of a Swedish strategy to achieve net-zero emissions by 2045 and net- negative thereafter [1]. However, biomass is a limited resource and the resource base, costs, trade- offs, abatement potential and usage are all intensively debated [43–48]. The uncertainties and versatility of biomass present a challenge for policy as well as for the affected investors and other stakeholders. The limited biomass resource can be used for many applications and cost-effective biomass usage strategies for achieving overall climate targets depend e.g. on available alternatives in each usage and on the availability of carbon storage. Thus, assessments of biomass usage demand a broad scope.

Biomass and CCS can be seen as being co-dependent for achieving climate targets; limitations on biomass affect the potential and cost of CCS and negative emissions, and limitations on CCS may alter the cost-effective usage of biomass for achieving climate targets. Analyses with a high technology detail which include all relevant energy sectors where the limited biomass can be used, and where these sectors are coupled are needed. Such analyses also need to include the relevant other, competing renewable alternatives. This is important in order to assess the long-term role of biomass usage in combination with CCS and not merely short-term fossil substitution benefits, which change over time and depend on other available alternatives in each sector.

Further, a high temporal detail is needed to assess the role of biomass as a complement to variable renewables. A high spatial detail enables a better depiction of regional supply and demand characteristics and transmission/transport issues. Uncertainty analyses of such detailed systems give a fuller picture of the robustness of results and especially biomass usage and are useful for decision makers. Analyses which adhere to all of these aspects are lacking.

A comprehensive analysis containing all of these aspects allows a holistic assessment of biomass usage. A focus on highlighting and quantifying the effect of inherent uncertainties over a span of future scenarios helps to analyse biomass usage strategies which hold over a manifold of possible futures and thus can be seen as being relatively robust. Such an analysis helps guide policy towards steering for areas where action is particularly necessary. The main research question to be assessed was the following:

- How does the combination of bioenergy with carbon capture and storage or utilization alter resource efficient and cost-effective biomass usage for achieving climate targets in the energy system?

This research question was sub-divided into several smaller research questions:

- How do uncertainties regarding biomass and carbon storage affect long-term resource efficient and cost-effective biomass usage in power, heat, transport and industry for achieving climate targets?
- How do these uncertainties alter the configuration of the overall energy system, how robust are different usages to the uncertainties and what policy implications can be derived?
- Under which circumstances is captured carbon more cost-effectively stored and when is it utilized for e.g. the manufacture of electrofuels?

The identified knowledge gap combined with concrete Swedish strategies for negative emissions provides an opportunity to be a prime mover, both in business as well as in research. This project will set biomass usage strategies in a larger context and thus help inform decision makers towards sustainable biomass resource usage. It also enables the competence building of the researchers involved within a timely subject of global importance, thus contributing to the global science community. The results will be used to inform policy in the form of policy briefs and a policy dialogue workshop with key Swedish stakeholders, and will also be disseminated within the reference group.

Genomförande

The project was subdivided into three working packages, as detailed below.

Markus Millinger led the project, with contributions from Fredrik Hedenus, Daniel Johansson and Lina Reichenberg.

The project was accompanied by a reference group, with which research questions, results and analyses were discussed:

- Stockholm Exergi - Fabian Levihn, Forskningschef Stockholm Exergi/Docent KTH
- Stora Enso - Conny Johansson, energichef Stora Enso
- Klimpo - Karolina Unger
- Preem - Cecilia Hellman

The project was carried out between June 2022 and December 2024.

WP1 - Data (jun 2022 - jun 2023)

In this working package, data on biomass, bioenergy conversion and CCUS were assembled and updated/supplemented in the model. The data includes: 1) A detailed parametrisation of bioenergy technologies with and without CCS/CCU, including fit of different biomass types to different processes. 2) Data on existing and planned point sources where BECCS is a viable option. 3) CO2 transport data (train, lorry, ship, pipeline), storage sites (including scale, scale-up, plans, costs/prices).

WP2 - Energy system modelling (sep 2022 - jun 2024)

The modelling was performed with the sector-coupled energy system model for Europe (PyPSA [49]). Analyses for the medium and long term (2030/2050) were performed, with an emphasis on sensitivity analysis and assessment for many parameter variations in order to assess the robustness of biomass usage strategies and the resulting energy system.

In this working package the model development was handled: 1) data from WP1 on e.g. integration of point-sources in the model, update of bioenergy technology configuration are integrated into the model, 2) methods are chosen/developed for especially the spatial handling of biomass and CO2 transport, 3) scenario and sensitivity analysis setup in close collaboration with WP3.

The working package determined the suitable level of spatial detail for Sweden, and for the rest of Europe (with a suitably lower detail), and sets up both the brownfield and greenfield analyses.

WP2 contributed to the open-source model development of the sector-coupled european energy system model PyPSA [49, 50] and handled communication with the international PyPSA community. Model runs were set up on the high-performance computing cluster C3SE at Chalmers University of Technology [51].

WP3 - Scenarios and analysis (jan 2023 - dec 2024)

This working package handled defining scenarios and sensitivity analyses and analysis of modelling results.

The sensitivity analyses were comprehensive and involved e.g. variations on biomass resource potentials, costs, carbon capture efficiency, transport option costs, storage availability and scale-up, solar and wind power deployment, transmission, electrification rate/sector coupling, weather years. Carbon storage deployment limitations and storage prices may affect usage pathways and were assessed. Policies such as emission targets, sectoral renewable targets, emission pricing etc. were explored.

This working package also handled the relation of the results and analysis to policy, and derived policy recommendations.

Energimyndigheten

Resultat

The first study, published in Nature Energy [52] with an accompanying policy brief [53], explored near-optimal solutions for biomass usage in the energy system. Biomass is a versatile renewable energy source with applications across the energy system, but it is a limited resource and its usage needs prioritisation. We use a sector-coupled European energy system model to explore near-optimal solutions for achieving emissions targets. We find that provision of biogenic carbon has higher value than bioenergy provision. Energy system costs increase by 20% if biomass is excluded at a net-negative (−110%) emissions target and by 14% at a net-zero target. Dispatchable bioelectricity covering ~1% of total electricity generation strengthens supply reliability. Otherwise, it is not crucial in which sector biomass is used, if combined with carbon capture to enable negative emissions and feedstock for e-fuel production. A shortage of renewable electricity or hydrogen supply primarily increases the value of using biomass for fuel production. Results are sensitive to upstream emissions of biomass, carbon sequestration capacity and costs of direct air capture.

Another study, published in Environmental Research Letters [54] explored the emerging potential of atmospheric methane removal (MR) as a complementary strategy to carbon dioxide removal (CDR) in climate mitigation pathways. Given methane's significant contribution to global warming and the challenges in reducing agricultural methane emissions, the study examines the conditions under which MR could become a cost-effective alternative to CDR. Using the ACC2-GET inte- grated climate-energy model, the analysis evaluates MR's cost and removal potential thresholds necessary to meet climate targets at lower or comparable abatement costs to bioenergy-based CDR (BECCS). Results indicate that MR could entirely replace BECCS if removal potentials reach 180–320 MtCH4/year (50–90% of current anthropogenic methane emissions) at unit costs ranging between $10,000 and $34,000 per ton of methane, depending on the climate target. Furthermore, substituting CDR with MR redistributes climate mitigation efforts across generations by delaying the burden, offering insights into the economic and temporal implications of deploying MR technologies.

A third study [55], accepted for publication in Environmental Research Letters, explored the effect of solvents and sorbents for carbon capture on energy system cost. Technical carbon dioxide removal through bioenergy with carbon capture (BECC) or direct air capture (DAC) plays a role in virtually all climate mitigation scenarios. Both of these technologies rely on the use of chemical solvents or sorbents in order to capture CO2. Lately, concerns have surfaced about the cost and energy implications of producing solvents and sorbents at scale. Here, we show that the production of chemical sorbents could have significant implications on system cost, energy use and material use depending on how much they are consumed. Among the three chemical sorbents investigated, namely monoethanolamine (MEA) for post-combustion carbon capture, potassium hydroxide (KOH) for liquid direct air capture and polyethylenimine-silica (PEI) for solid sorbent direct air capture, we found that solid sorbent production for direct air capture represents the highest uncertainties for the system. At the high range of solid sorbent consumption, total energy system cost increased by up to 6.5% compared to the base case, while effects for other options were small to negligible. Scale-up of material production capacities was also substantial for MEA and PEI. While PEI has the advantage of requiring a lower sorbent regeneration temperature than KOH, the potential production cost may outweigh these benefits. There is thus a trade-off between the advantages and the additional cost uncertainty regarding sorbents. Implications of sorbent consumption for carbon capture technologies should be considered more thoroughly in scenarios relying on solid sorbent direct air capture.

Diskussion

To meet climate targets, net-negative emissions in the energy system are likely necessary, with direct air capture and bioenergy with carbon capture and utilization or storage seen as important technology options. While bioenergy can be associated with both positive and negative environmental, social and economic effects, concerns about negative impacts have led the European Union to cap biofuels from food and feed crops and to increasingly emphasize the use of waste and residue resources. Further policy development needs to be informed about intersectoral competition and effective use of biomass resources alongside emerging options such as direct air capture, low-carbon electrolysis and e-fuels.

Biomass associated with low upstream emissions offers cost-effective renewable carbon for negative emissions and production of chemicals, aviation and shipping fuels, reducing the need for more costly options like direct air capture. Policy support for sustainable biomass use alongside emerging technologies reduces energy system costs and the risk of missing emissions targets.

Publikationslista

The results of the following publications are summarised under results above:

Millinger, M., Hedenus, F., Zeyen, E., Neumann, F., Reichenberg, L., Berndes, G. (2025): Diversity of biomass usage pathways to achieve emissions targets in the European energy system. Nature Energy. 10.1038/s41560-024-01693-6

Millinger, M., Hedenus, F., Zeyen, E., Neumann, F., Reichenberg, L., Berndes, G. (2025): Biomass exclusion must be weighed against benefits of carbon supply in European energy system. Nature Energy. 10.1038/s41560-024-01685-6

Chanal, V., Humpage, S., Millinger, M. (accepted for publication): Accounting for carbon capture solvent cost and energy demand in the energy system. Environmental Research Letters. Pre-print: 10.48550/arXiv.2411.09520

Gaucher, Y., Tanaka, K., Johansson, D. J. A., Boucher, O., Ciais, P. (2025). Potential and costs required for methane removal to compete with BECCS as a mitigation option. Environmental Research letters 20, 024034. 0.1088/1748-9326/ada813

Conferences:

• Millinger, M. (2024): Systemanalys av biomassa och koldioxidavskiljning över energisektorerna. Bio+ conference, Energimyndigheten, Stockholm, 5 Sep 2024.

• Millinger, M. (2024): Diversity of biomass usage pathways to achieve emissions targets in the European energy system. International Energy Workshop, Bonn, 26-28 June 2024.

• Millinger, M. (2024): Diversity of biomass usage pathways to achieve emissions targets in the European energy system. International Conference on Negative CO2 Emissions 2024, Oxford, 18-21 June 2024.

• Millinger, M. (2023): Considerations on the priority of biomass use in future energy systems. IEA Bioenergy ExCo Workshop “Bioenergy in a Net Zero Future”, Lyon, 19 Oct. (invited presentation)

• Millinger, M., Hedenus, F., Reichenberg, L., Zeyen, E., Neumann, F., Berndes, G. (2023): Near-Optimal Analysis of Biomass Usage to Achieve Negative

Emissions in the European Energy System. 22nd Wind & Solar Integration Workshop, Copenhagen 26-28 Sep.

Model development carried out in this project is available open source with an MIT license. Model details on biomass usage, industry and carbon capture have been enhanced and represent state-of-the-art in energy systems modelling, as outlined in [52].

Referenser, källor

[1] Å.-B. Karlsson, Vägen till en klimatpositiv framtid: Betänkande av Klimatpolitiska vägvalsutredningen, 2020.

[2] K. Calvin, A. Cowie, G. Berndes, A. Arneth, F. Cherubini, J. Portugal-Pereira, G. Grassi, J. House, F. X. Johnson, A. Popp, M. Rounsevell, R. Slade, P. Smith, Bioenergy for climate change mitigation: scale and sustainability, GCB Bioenergy (may 2021). doi:10.1111/gcbb.12863.

[3] A. Cowie, G. Berndes, N. Bentsen, M. Brandão, F. Cherubini, G. Egnell, B. George, L. Gustavsson, M. Hanewinkel, Z. Harris, F. Johnsson, H. Junginger, K. Kline, K. Koponen, J. Koppejan, F. Kraxner, P. Lamers, S. Majer, E. Marland, G. Nabuurs, L. Pelkmans, R. Sathre, M. Schaub, C. Smith, S. Soimakallio, F. Van Der Hilst, J. Woods, F. Ximenes, Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy, GCB Bioenergy 17 (2021) gcbb.12844. doi:10.1111/gcbb.12844.

[4] F. Creutzig, Economic and ecological views on climate change mitigation with bioenergy and negative emissions, GCB Bioenergy 8 (1) (2016) 4–10. doi:10.1111/gcbb.12235.

[5] K. Anderson, G. Peters, The trouble with negative emissions, Science 354 (6309) (2016) 182–183. doi:10.1126/science.aah4567.

[6] S. Fuss, J. G. Canadell, G. P. Peters, M. Tavoni, R. M. Andrew, P. Ciais, R. B. Jackson, C. D. Jones, F. Kraxner, N. Nakicenovic, C. Le Quéré, M. R. Raupach, A. Sharifi, P. Smith, Y. Yamagata, Betting on negative emissions, Nature Climate Change 4 (10) (2014) 850–853. doi:10.1038/nclimate2392.

[7] V. Smil, Energy myths and realities: bringing science to the energy policy debate, AEI Press, 2011.

[8] M. Millinger, P. Tafarte, M. Jordan, A. Hahn, K. Meisel, D. Thrän, Electrofuels from excess renewable electricity at high variable renewable shares: cost, greenhouse gas abatement, carbon use and competition, Sustainable Energy and Fuels 5 (3) (2021). doi:10.1039/d0se01067g.

[9] F. Ueckerdt, C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, G. Luderer, Potential and risks of hydrogenbased e-fuels in climate change mitigation, Nature Climate Change (2021). doi:10.1038/s41558-021-01032-7.

[10] M. Lehtveer, S. Brynolf, M. Grahn, What Future for Electrofuels in Transport? Analysis of Cost Competitiveness in Global Climate Mitigation, Environmental Science and Technology 53 (3) (2019) 1690–1697. doi:10.1021/acs.est.8b05243.

[11] V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. Matthews, Y. Chen, X. Zhou, M. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield, Global Warming of 1.5C. An IPCC Special Report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, Intergovernmental Panel on Climate Change, 2018. https://www.ipcc.ch/sr15/

[12] V. Daioglou, S. K. Rose, N. Bauer, A. Kitous, M. Muratori, F. Sano, S. Fujimori, M. J. Gidden, E. Kato, K. Keramidas, D. Klein, F. Leblanc, J. Tsutsui, M. Wise, D. P. van Vuuren, Bioenergy technologies in long-run climate change mitigation: results from the EMF-33 study, Climatic Change 163 (3) (2020) 1603–1620. doi:10.1007/s10584-020-02799-y.

[13] J. Rogelj, A. Popp, K. V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa, G. Marangoni, V. Krey, E. Kriegler, K. Riahi, D. P. van Vuuren, J. Doelman, L. Drouet, J. Edmonds, O. Fricko, M. Harmsen, P. Havlík, F. Humpenöder, E. Stehfest, M. Tavoni, Scenarios towards limiting global mean temperature increase below 1.5 °C, Nature Climate Change 8 (4) (2018) 325–332. doi:10.1038/s41558-018-0091-3.

[14] N. Bauer, S. K. Rose, S. Fujimori, D. P. van Vuuren, J. Weyant, M. Wise, Y. Cui, V. Daioglou, M. J. Gidden, E. Kato, A. Kitous, F. Leblanc, R. Sands, F. Sano, J. Strefler, J. Tsutsui, R. Bibas, O. Fricko, T. Hasegawa, D. Klein, A. Kurosawa, S. Mima, M. Muratori, Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison, Climatic Change 163 (3) (2020) 1553–1568. doi:10.1007/s10584-018-2226-y.

[15] C. Azar, D. J. Johansson, N. Mattsson, Meeting global temperature targets - The role of bioenergy with carbon capture and storage, Environmental Research Letters 8 (3) (2013). doi:10.1088/1748-9326/8/3/034004.

[16] F. Creutzig, G. Nemet, J. C. Minx, C. Change, G. Nemet, Climate change mitigation easier than suggested by models (2021) 1–17.

[17] M. Victoria, N. Haegel, I. M. Peters, R. Sinton, A. Jäger-Waldau, C. del Cañizo, C. Breyer, M. Stocks, A. Blakers, I. Kaizuka, K. Komoto, A. Smets, Solar photovoltaics is ready to power a sustainable future, Joule (2021) 1–16doi:10.1016/j.joule.2021.03.005.

[18] F. Creutzig, P. Agoston, J. C. Goldschmidt, G. Luderer, G. Nemet, R. C. Pietzcker, The underestimated potential of solar energy to mitigate climate change, Nature Energy 2 (9) (2017). doi:10.1038/nenergy.2017.140.

[19] M. Lehtveer, A. Emanuelsson, BECCS and DACCS as Negative Emission Providers in an Intermittent Electricity System: Why Levelized Cost of Carbon May Be a Misleading Measure for Policy Decisions, Frontiers in Climate 3 (March) (2021) 1–12. doi:10.3389/fclim.2021.647276.

[20] G. Realmonte, L. Drouet, A. Gambhir, J. Glynn, A. Hawkes, A. C. Köberle, M. Tavoni, An inter-model assessment of the role of direct air capture in deep mitigation pathways, Nature Communications 10 (1) (2019) 1–12. doi:10.1038/s41467-019-10842-5.

[21] F. Creutzig, C. Breyer, J. Hilaire, J. Minx, G. P. Peters, R. Socolow, The mutual dependence of negative emission technologies and energy systems, Energy and Environmental Science 12 (6) (2019) 1805–1817. doi:10.1039/c8ee03682a.

[22] C. Breyer, M. Fasihi, C. Bajamundi, F. Creutzig, Direct Air Capture of CO2: A Key Technology for Ambitious Climate Change Mitigation, Joule 3 (9) (2019) 2053–2057. doi:10.1016/j.joule.2019.08.010. https://doi.org/10.1016/j.joule.2019.08.010

[23] A. Grubler, C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. L. McCollum, N. D. Rao, K. Riahi, J. Rogelj, S. De Stercke, J. Cullen, S. Frank, O. Fricko, F. Guo, M. Gidden, P. Havlík, D. Huppmann, G. Kiesewetter, P. Rafaj, W. Schoepp, H. Valin, A low energy demand scenario for meeting the 1.5 °c target and sustainable development goals without negative emission technologies, Nature Energy 3 (6) (2018) 515–527. doi:10.1038/s41560-018-0172-6.

[24] M. Child, C. Kemfert, D. Bogdanov, C. Breyer, Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe, Renewable Energy 139 (2019) 80–101. doi:10.1016/j.renene.2019.02.077.

[25] D. Bogdanov, J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, A. S. Oyewo, L. de Souza Noel Simas Barbosa, C. Breyer, Radical transformation pathway towards sustainable electricity via evolutionary steps, Nature Communications 10 (1) (2019) 1077. doi:10.1038/s41467-019-08855-1.

[26] D. Bogdanov, M. Ram, A. Aghahosseini, A. Gulagi, A. S. Oyewo, M. Child, U. Caldera, K. Sadovskaia, J. Farfan, L. De Souza Noel Simas Barbosa, M. Fasihi, S. Khalili, T. Traber, C. Breyer, Low-cost renewable electricity as the key driver of the global energy transition towards sustainability, Energy 227 (2021) 120467. doi:10.1016/j.energy.2021.120467.

[27] M. Z. Jacobson, M. A. Delucchi, Z. A. Bauer, S. C. Goodman, W. E. Chapman, M. A. Cameron, C. Bozonnat, L. Chobadi, H. A. Clonts, P. Enevoldsen, J. R. Erwin, S. N. Fobi, O. K. Goldstrom, E. M. Hennessy, J. Liu, J. Lo, C. B. Meyer, S. B. Morris, K. R. Moy, P. L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M. A. Sontag, J. Wang, E. Weiner, A. S. Yachanin, 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World, Joule 1 (1) (2017) 108–121. doi:10.1016/j.joule.2017.07.005.

[28] M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, B. A. Frew, The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims, Proceedings of the National Academy of Sciences of the United States of America 114 (26) (2017) E5021–E5023. doi:10.1073/pnas.1708069114.

[29] C. T. Clack, S. A. Qvist, J. Apt, M. Bazilian, A. R. Brandt, K. Caldeira, S. J. Davis, V. Diakov, M. A. Handschy, P. D. Hines, P. Jaramillo, D. M. Kammen, J. C. Long, M. G. Morgan, A. Reed, V. Sivaram, J. Sweeney, G. R. Tynan, D. G. Victor, J. P. Weyant, J. F. Whitacre, Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar, Proceedings of the National Academy of Sciences of the United States of America 114 (26) (2017) 6722–6727. doi:10.1073/pnas.1610381114.

[30] A. Purkus, Concepts and Instruments for a Rational Bioenergy Policy, Vol. 55 of Lecture Notes in Energy, Springer International Publishing, Cham, 2016. doi:10.1007/978-3-319-31135-7.

[31] N. Bento, C. Wilson, Measuring the duration of formative phases for energy technologies, Environmental Innovation and Societal Transitions 21 (2016) 95–112. doi:10.1016/j.eist.2016.04.004.

[32] CinfraCap, CinfraCap - flytande koldioxids väg till hamnen (2021). URL https://www.goteborgshamn.se/hamnens-projekt/cinfracap/

[33] Stockholm Exergi, Bio-CCS - Stockholm Exergi (2021). URL https://www.stockholmexergi.se/om-stockholm-exergi/about-stockholm-exergi/negative-emissions/bioccs/

[34] Cementa, CCS - fånga och lagra koldioxid, CO2 (2021). URL https://www.cementa.se/sv/koldioxidavskiljning-och-lagring-ccs

[35] C. Odén, Ny teknik kan fånga koldioxid i skorstenen - P4 Gävleborg | Sveriges Radio (2019). URL https://sverigesradio.se/artikel/7325981

[36] Northern Lights, Northern Lights (2021). URL https://northernlightsccs.com/

[37] Jämtkraft, Goda resultat för produktion av förnybart flygbränsle i Östersund | Jämtkraft (2021). https://www.jamtkraft.se/om-jamtkraft/nyhetsrum/goda-resultat-for-produktion-av-fornybartflygbransle-i-ostersund/

[38] A. Fagerström, D. Grahn, S. Lundberg, S. Ghosh, D. Creaser, L. Olsson, O. Abdelaziz, O. Wallberg, C. Hulteberg, S. Poulikidou, A. Lewrén, T. Rydberg, M. Martin, S. Anderson, J. Hansson, A. Hjort, Large scale bio electro jet fuel production integration at CHP-plant in Östersund , Sweden, IVL Swedish Environmental Research Institute Ltd., 2021.

[39] A. Fagerström, S. Klugman, S. Poulikidou, S. Anderson, Biojet Östersund – Supplementary studies and international cooperation Supplementary studies to the project: Large scale Bio-Electro-Jet fuel production integration at CHP-plant in Östersund, Sweden, IVL Swedish Environmental Research Institute Ltd., 2021.

[40] Liquid Wind, eMethanol — Liquid Wind - eMPowering our Future. (2021). https://www.liquidwind.se/emethanol

[41] Södra, Södra participates in electro-fuels research project (2019). https://www.sodra.com/en/se/om-sodra/news2/2019/Sodra-participates-in-electro-fuels-researchproject/

[42] Project AIR, Project AIR (2021). https://projectair.se/en/

[43] L. Röstlund, P. Alestig, A. Urisman Otto, M. Westholm, 500 forskare uppmanar till att stoppa stöd till biobränsle - DN.SE (feb 2021). https://www.dn.se/sverige/forskare-uppmanar-usa-och-eu-sluta-stodja-biobranslen/

[44] L. Röstlund, M. Westholm, Klimatfrågan splittrar svenska skogsforskare - DN.SE (feb 2021). https://www.dn.se/sverige/klimatet-fragan-som-splittrar-den-svenska-skogsforskningen/

[45] S. Wirsenius, T. D. Searchinger, DN Debatt. ”Satsningen på biodrivmedel ökar koldioxidutsläppen” - DN.SE (dec 2018). https://www.dn.se/debatt/satsningen-pa-biodrivmedel-okar-koldioxidutslappen/

[46] P. Högberg, J. Fridman, ”EU-forskares uppgifter om skogsbruk var gravt felaktiga” - DN.SE (apr 2021). https://www.dn.se/debatt/eu-forskares-uppgifter-om-skogsbruk-var-gravt-felaktiga/

[47] S. Axelsson, L. Ek, P. Holland, M. Kagevik, H. Wahl, DN Debatt. ”Elbilssatsning räcker inte för att nå klimatmålen” - DN.SE (jun 2020). https://www.dn.se/debatt/elbilssatsning-racker-inte-for-att-na-klimatmalen/

[48] A. Urisman Otto, L. Röstlund, A. Hansson, Biobränsle: Skog huggs ner för att eldas som bränsle - DN.SE (apr 2021). https://www.dn.se/sverige/har-huggs-skog-ner-for-att-varma-svenska-hem/

[49] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, M. Greiner, Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system, Energy 160 (2018) 720–739. doi:10.1016/j.energy.2018.06.222.

[50] T. Brown, M. Victoria, E. Zeyen, PyPSA-Eur-Sec: A Sector-Coupled Open Optimisation Model of the European Energy System — PyPSA-Eur-Sec 0.5.0 documentation (2021). https://pypsa-eur-sec.readthedocs.io/en/latest/

[51] C3SE, Home - C3SE (2021). https://www.c3se.chalmers.se/

[52] M. Millinger, F. Hedenus, E. Zeyen, F. Neumann, L. Reichenberg, G. Berndes, Diversity of biomass usage pathways to achieve emissions targets in the European energy system, Nature Energy (2025). doi:10.1038/s41560-024-01693-6.

[53] M. Millinger, F. Hedenus, E. Zeyen, F. Neumann, L. Reichenberg, G. Berndes, Biomass exclusion must be weighed against benefits of carbon supply in

European energy system, Nature Energy (2025). doi:10.1038/s41560-024-01685-6.

[54] Y. Gaucher, K. Tanaka, D. J. Johansson, O. Boucher, P. Ciais, Potential and costs required for methane removal to compete with BECCS as a mitigation option, Environmental Research Letters 20 (2) (2025). doi:10.1088/1748-9326/ada813.

[55] V. Chanal, S. Humpage, M. Millinger, Accounting for carbon capture solvent cost and energy demand in the energy system, Environmental Research Letters (2025).