The role of energy cost in assessing the feasibility of carbon dioxide mitigation options

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A range of climate change mitigation measures is being proposed to meet a well below 2 °C global temperature rise. However, the amount of additional energy required by some proposed carbon dioxide (CO₂) mitigation options make them inviable as routes to mitigation, especially if they are to be deployed at global scale. Here, we provide a systematic review and assessment of different mitigation options in terms of their energy requirement. We assess the relative effectiveness of several CO₂ mitigation routes by calculating the energy cost of carbon abatement (kilowatt-hour spent per kg CO₂ mitigated). We consider decarbonising electricity, heat, chemicals, and fuels; and also capturing CO₂ from air. Among the routes considered, switching to renewable energy technologies offer the most energy-effective mitigation (0 – 0.53 kWh/kg-CO₂) while carbon removal approaches are more energy intensive (0.32 – 2.93 kWh/kg-CO₂). Our analysis stresses the need for mitigation studies to accurately capture the energy cost of mitigation technologies, especially when considering carbon embedding and removal technologies that are both resource and energy intensive.

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In efforts to meet global emissions reductions targets, policymakers are considering emission reduction measures other than simply *avoiding* carbon dioxide (CO₂) emissions such as by replacing fossil fuels with renewable alternatives and applying efficiency improvements¹. The additional mitigation options include ways of capturing and *using* (or “embedding”) already emitted CO₂ in the manufacture of fuels, plastics and construction materials, and *removing* CO₂ from the atmosphere using negative emission technologies such as by direct air capture combined with carbon storage (DACCS) or by bioenergy for electricity or fuel together with carbon capture and storage (BECCS). Most embedding and removal options have not been deployed at scale, but BECCS², and recently, DACCS^{3,4}, have been included as options in the integrated assessment models (IAMs) used to simulate very low carbon pathways^{5,6}. In fact, DACCS, and BECCS in particular, appear central in climate mitigation policy pathways to hold global warming to levels below 1.5°C because of their modelled (though not proven) effectiveness in removing CO₂. This has stimulated interest, among governments, industry and policymakers, in developing such mitigation options at a functionally relevant scale^{7–10}.

One critical aspect that must be considered before any technology gets deployed at scale is the amount of energy invested in any mitigation option. Energy is a critical metric for several reasons: first, atmospheric CO₂ is both dilute and stable, so processes that involve collecting and/or converting CO₂ into a chemically less stable form have a significant energy cost^{2,3}. Second, unlike price or monetary cost, the amount of energy required for any process has a robust and universal value in terms of the useful work that it represents. Third, global energy requirements are, currently, strongly correlated to CO₂ emissions and implementation of any technology that increases energy requirements is likely to increase emissions to a corresponding degree and hence increase the mitigation challenge. Implementing an energy intensive mitigation option would thus increase the global energy budget and therefore global

emissions, since the countries would have to deploy large amounts of new energy generation capacity. Such energy requirements might make an option detrimental to the mitigation goals of reducing global emissions and environmental impact, especially if it is implemented using an energy source that also depletes other critical resources such as land and water. A consistent analysis of the energy costs of any mitigation option, whether avoiding, embedding or removing CO₂, is therefore essential before pursuing any option at global scale.

Whilst measures such as energy return on investment (EROI) can be used to quantify the energy costs of mitigation technologies that produce an energy vector such as fuel or electricity^{11,12}, EROI metric is not a relevant comparative measure for mitigation options that remove or embed carbon rather than supplying energy. In such circumstances another metric is required. Comparison of the energy requirements of low-carbon energy technologies is complicated by the intrinsically different quality of energy carriers such as electricity and thermal fuels¹³. Nevertheless, some recent studies have begun to introduce metrics to compare different technologies in terms of the energy consumption per unit of fossil feedstock replaced¹⁴ or energy invested per unit of carbon removed (for BECCS and DACCS)³, while others have begun to address energy costs explicitly within IAMs and low-carbon pathway models¹⁵⁻¹⁷. None of these approaches has yet offered a comprehensive and consistent framework for comparing the energy costs of different mitigation options, such as avoidance with embedding or removal.

Here, we propose such a metric, the net energy invested per unit mass of net CO₂ mitigated, referred to as “Carbon Abatement Energy Cost” (CAEC), that only requires basic carbon and energy accounting. We show how CAEC can be used as a tool to compare the CO₂ mitigation performance of inherently different technologies, and how some options, that may be modelled as favourable in terms of monetary cost, become highly unfavourable when energy costs are considered. Such indicative metrics can become invaluable to help

51 policymakers prioritise investing resources into the most effective mitigation technologies
52 among various emerging options.

53 **Energy cost of CO₂ mitigation options**

54 Evaluating the environmental impacts of an action requires system boundary definition
55 within which the consequences of the action are traceable. Here, we quantify the net CO₂
56 reduction potential of a mitigation option and the energy required to achieve this reduction.
57 Thus, we track the net energy requirements that would be required by using a given process
58 and the associated relative change in CO₂ emissions enabled by this process (Eq. 1–4 in
59 Methods and Fig. 1).

Fig. 1 | **Generalised energy and carbon balances of a process or a technology when considering CO₂ mitigation potential.** The components shown here represent the most generalised case and not every process or technology would necessarily have all components. For instance, DACCS does not produce an energy yield but it requires energy that would result in additional CO₂ to get released into the atmosphere. It removes atmospheric CO₂, but it also results in CO₂ emissions when its components and chemicals are manufactured.

60 Alternative routes to an incumbent technology (“reference”) providing a service or
61 product generally differ in terms of their energy requirements and associated emissions (Fig.
62 2a). For instance, an alternative route might deliver an identical product or service as the

reference technology using less energy and result in lower emissions (Alternative 1 in Fig. 2a). Conversely, another route (Alternative 2 in Fig. 2a) might result in even lower emissions but might require substantially more energy to do so. If we consider a conventional method as our reference, then the switch to an alternative method could result in different outcomes in terms of climate mitigation potential (Fig. 2b).

Fig. 2 | Mitigation technologies according to their energy and carbon balance. E_{REF} and C_{REF} are energy and carbon balance, respectively, for the reference process. **a**, Alternative routes to provide a service or manufacture a product. **b**, Processes according to their mitigation effectiveness in terms of their energy use.

Most alternative options usually require more energy to reduce the carbon footprint of a service or product than the reference (Region IV), but if an alternative option requires significantly more energy (Region V), then it might be infeasible or even detrimental to adopt it. If an innovative alternative option reduces both the energy requirement and emissions footprint of a product or service (other potential impacts aside), switching can be considered as advantageous (Region III). In addition, options that reduce the energy requirement but lead to more emissions (Region II) might still be effective in mitigation in a larger context if this saved energy can be used elsewhere to replace another process with even higher emissions intensity thus resulting in a net reduction in emissions. Therefore, it is important to consider

the energy requirements of switching to alternative routes to technological processes currently used.

Mitigation option categories

Fig. 3 | Mitigation option categories and representative examples. Moving from a conventional process (that requires E_{REF} and C_{REF} in Fig. 2) to an alternative option entails different energetic requirements and results in different CO_2 emissions. Not all energy and CO_2 inputs and outputs are illustrated above for readability. **a**, Carbon avoidance, e.g. switching from a coal-fired thermal power station to photovoltaic power station. **b**, Carbon embedding, e.g. replacing carbon monoxide with CO_2 feedstock in methanol synthesis. **c**, Carbon removal, e.g. growing bio-energy crops and sequestering CO_2 upon burning them for energy.

In our evaluation, each process or technology is treated as a system to which we apply mass and energy balances comprising energy inputs, energy outputs, and atmospheric CO_2 removal and/or emission flows. This approach can be applied to processes that produce something other than energy, such as CO_2 use in polymer synthesis or fuel production, and to technologies such as DACCS that may result in net CO_2 removal. It can also be applied to the substitution of one process or technology by another. Mitigation options, currently and potentially available, are grouped into three categories: carbon avoidance, carbon embedding, and carbon removal (Fig. 3).

In *carbon avoidance*, an alternative technology eliminates the need for the fossil feedstock or fossil fuel, on which the conventional practice depends, while providing the

same product or service. Examples include replacing the electricity generated by fossil fuel by renewable power-generation technologies (e.g., solar, wind), and replacing hydrocarbon fuels for vehicles by other fuels (e.g., hydrogen, ammonia) produced using renewable energy. Most alternatives in the carbon avoidance category typically require low-carbon energy generation to replace fossil fuel-based generation. However, there are also other options such as energy efficiency measures like improved thermal insulation, which reduce energy and associated emissions without requiring additional low-carbon energy generation.

Fig. 4 | Energetic overview of carbon embedding processes. CO₂ can be combined with a high energy material such as hydrogen to manufacture products such as methanol. For any conversion of CO₂ into a higher energy product, such as methanol or synthetic gas, additional energy is needed to produce the high energy co-reactant (hydrogen in this example). That extra energy must be generated with a low carbon technology (renewable or nuclear power) to avoid a net increase in atmospheric CO₂ levels. Note that embedded CO₂ would be released back to the atmosphere at the end of lifetime of the higher energy product.

The second category, *carbon embedding* (sometimes referred to as carbon capture and use, CCU), includes processes whereby CO₂ is used as a feedstock in the production of materials and fuels. Options include methanol synthesis from CO₂ through hydrogenation¹⁸, the co-polymerization of CO₂ with propylene oxide to produce polyols¹⁹, the reverse water-gas shift reaction between CO₂ and hydrogen to produce synthetic gas, and the reaction of

CO₂ with hydrogen to produce methane²⁰. Because of thermodynamic stability of the CO₂ molecule there is usually a need for significant energy input from high energy chemicals and often heat to drive the relevant chemical reactions (Fig. 4). These energy inputs (the high energy chemicals and heat) must be produced using low-carbon energy for carbon embedding to be effective as a carbon mitigation process. Another consideration is that the products that embed CO₂ within their chemical structure will eventually release CO₂ back into the atmosphere at the end of their lifetime. This lifetime depends on the product, e.g. liquid fuels can provide storage for days at the most, and polymers for up to a few years. Thus, carbon embedding will not contribute to mitigation without long-term stability of the product; the processes being considered here do not fulfil this criterion. Nevertheless, we have still included them in the present treatment as they are often discussed in the context of low-carbon transition and carbon mitigation policy.

Both *carbon avoidance* and *carbon embedding* can reduce emissions but cannot result in net negative emissions. The third category, *carbon removal*, includes methods that increase carbon sequestration capability of natural ecosystems (e.g., through reforestation, afforestation, or soil carbon sequestration) and negative emission technologies that sequester atmospheric CO₂ with the aim of storing it for long-term in structures like geological formations. Among the latter category of negative emission technologies, two options are being discussed extensively in scientific and policy related literature due to their reported potentially high carbon removal capability, namely BECCS and DACCS²¹. BECCS involves the production of biomass (bio-energy crops, wood etc.) that absorbs CO₂ from the atmosphere as the crops grow, and the combustion of this biomass for energy or for producing liquid fuels whilst sequestering and storing at least some of the resulting CO₂ emissions. DACCS technologies, on the other hand, directly capture CO₂ from the atmosphere through a range of different processes, e.g. uses chemicals such as amine or

strong base solutions to remove CO₂. In the case of aqueous alkali solutions, the reaction produces solid carbonates, which are then heated to high temperatures to release CO₂. The resulting CO₂ stream is collected and compressed for long-term storage²².

Options in all three categories have vastly different energetic requirements and associated CO₂ mitigation potential, which affect their viability as mitigation options. The Carbon Abatement Energy Cost (CAEC) we propose is a broad but comprehensive means to compare all options in terms of their ability to mitigate net CO₂ per unit of net energy invested.

Mitigation options considered in this study

Table 1 lists the set of mitigation options involving carbon avoidance, embedding or removal that are considered in this study. The alternative routes for each product or service listed represent different ways of transforming current industrial production or energy conversion practices to reduce net CO₂ emissions. These products and services cover a variety of sectors including electricity, heat, fuels and chemicals. An example of an ongoing transformation is the transition towards a low-carbon electricity infrastructure, mostly through adding solar and wind power generation whilst retiring older fossil-fired power plants. Thus, as an example of a proven effective emissions mitigation strategy, we firstly consider switching from fossil-fired generation (coal or natural gas) to low-carbon electricity generation (nuclear, solar photovoltaic and wind power). Low-carbon electricity generation is important not only because the electricity sector has to be decarbonised but also because many other mitigation options depend on readily available low-carbon electricity and are ineffective with a fossil-fuel-driven supply chain^{23,24}.

Table 1 | Products and services belonging to various mitigation categories examined in this study. In each case, replacing current practice (i.e., reference route) by the alternative route would result in net emissions reductions. Note that the CAEC will depend on the process we consider; replacing process A by process B will result in a CAEC that is, in general, different from that due to simply introducing process B. “CCS” stands for the technologies that provide carbon capture and storage.

Service Category	Product or Service	Current Practice	Alternative Option	Mitigation Category	How CAEC is determined?
Electricity	Electricity	Combusting fossil feedstock (coal or natural gas)	Renewable or nuclear power	Carbon Avoidance	Comparing alternative option against conventional practice (Eq. 4, Methods)
	Electricity with CCS	Combustion of fossil fuels (coal or natural gas) with CCS	Biomass combustion with CCS	Carbon Removal	Comparing alternative option against conventional practice (Eq. 2, Methods)
Heat	Hydrogen	Reformation or gasification of fossil feedstock	Water electrolysis powered by renewable or nuclear power	Carbon Avoidance	
Fuel	Diesel with CCS	Distillation of crude oil	Biomass-based Fischer-Tropsch synthesis with CCS	Carbon Removal	Calculating CO ₂ mitigation performance of
	Methanol	Hydrogenation of synthesis gas	Hydrogenation of CO ₂	Carbon Embedding	

Chemicals	Dimethyl Carbonate	Phosgenation or oxidative carbonylation of methanol	Transesterification of ethylene carbonate	Carbon Embedding	introducing alternative option alone (Eq. 1, Methods)
	Polyol synthesis	Propylene oxide-based synthesis	Co-polymerization of CO ₂	Carbon Embedding	
Removal	Direct air capture	None	Absorption or adsorption with a sorbent	Carbon Removal	

We consider hydrogen because decarbonising its production impacts the efficacy of many of the options in Table 1. In addition, changing how hydrogen is produced today is extremely important for two other reasons: (1) currently 96% of hydrogen production worldwide relies on natural gas, oil and coal²⁵ resulting in emissions of about 0.83 Gt-CO₂-eq per year²⁶ (more than 2% of current global emissions), and (2) hydrogen is essential for CO₂-based chemical and fuel production techniques as well as being considered as a fuel in its own right. In fact, low-carbon hydrogen is envisaged as a direct replacement of natural gas in some applications and has featured prominently in recent transition pathways for the decarbonisation of heat across sectors, including the industrial sector, which is considered the most challenging²⁷. This is important because heat as a final energy demand in most developed countries accounts for more than twice the final energy demand (largely, coming from fossil fuel) of electricity generation²⁸.

Once hydrogen production is decarbonised in a sustainable way, several routes for CO₂ use, which enable the production of liquid hydrocarbons from CO₂ but require decarbonised hydrogen supplies, might become possible as mitigation routes, albeit with an energy penalty. One such example is methanol, which can be synthesized using hydrogen and

CO₂ (Eq. 5). Currently methanol is widely used as a feedstock for the chemical industry to produce compounds such as formaldehyde or acetic acid, but methanol can be used as a liquid fuel, or, for instance, it could also be used to obtain dimethyl carbonate, a chemical with many applications, while embedding additional CO₂ in the process.

Polymer synthesis from CO₂ as a feedstock is proposed as an option for achieving greenhouse gas savings at industrial scale²⁹. We include in our analysis the case of polycarbonate polyols, where part of the propylene oxide needed in the conventional process can be replaced by CO₂²⁰.

Finally, we consider two carbon removal options that are considered to have the highest mitigation potential among negative emission technologies²¹. Firstly, we look at DACCS, which reacts atmospheric CO₂ with solutions of strong alkali solutions, such as sodium hydroxide (NaOH) and potassium hydroxide (KOH). Secondly, we consider two types of BECCS. The first type produces electricity using biomass as feedstock while capturing the CO₂ released during biomass combustion. The second type produces diesel from biomass using Fischer-Tropsch process, in which the CO₂ stream is captured and sequestered during the biomass gasification step of the biodiesel production.

CAEC of mitigation routes

Now, we turn our attention to chemical conversion processes and life cycle assessment (LCA) studies in order to determine the CAEC of each route. Such studies account for the electricity, thermal and other resource requirements at each stage and estimate associated greenhouse gas emissions. In order to determine CAEC for the mitigation options listed in Table 1, we reviewed published LCA studies for each technology. Details of this literature review and on how the CAEC was determined in each case are provided in the supplementary information. In order to demonstrate our approach, we first provide a detailed account of the analysis for one option from Table 1, low-carbon hydrogen production.

The energy cost and associated emissions for producing compressed hydrogen gas are shown in Fig. 5. Here we choose steam methane reforming as the reference case, where methane is reacted with steam to produce carbon monoxide and hydrogen. We compare the reference case against two low-carbon production routes: (1) electrolysis of water to hydrogen, which is a technologically (if not economically) mature process, using solar or wind power, and (2) thermochemical water splitting and high-temperature electrolysis using nuclear power.

Fig. 5 | CAEC of compressed hydrogen gas production. a, Energy cost and associated emissions expressed in carbon dioxide equivalent (CO₂-eq) for producing compressed hydrogen gas as reported in process and life cycle assessment studies. **b,** CAEC for each alternative route.

The average energy cost and emissions intensity of steam methane reforming (shown as red square in Fig. 5a) is approximately 182 MJ per kg of hydrogen and 12 kg CO₂-eq per kg of hydrogen, respectively. If compressed hydrogen were produced industrially using solar, wind or nuclear power instead, it would result in comparable or higher energy expenditure but reduce greenhouse gas emissions by an order of magnitude. The CAEC of each alternative technology route is determined by evaluating the additional energy requirement of switching to an alternative and dividing this energy cost by reductions in emissions. These values are shown in Fig. 5b. The arithmetic averages for switching to decarbonised routes

(solar and wind, or nuclear) are 0.53 and 1.36 kWh per kg CO₂-eq, respectively, although we observe a noteworthy spread. Here we also note that, other factors notwithstanding, solar and wind routes are about 60% more energy effective than nuclear in producing compressed hydrogen while mitigating the same amount of CO₂-eq. Allowing this type of direct comparison in terms of CO₂ mitigation effectiveness is one of the main benefits of having a metric such as the CAEC.

Following the same steps illustrated above, we investigated LCA and process studies of all mitigation routes listed in Table 1. The CAEC for each mitigation route is shown in Fig. 6 and detailed calculations are given in the supplementary information. The energy needed to embed or remove CO₂-eq from the atmosphere in carbon embedding routes and DACCS is not compared against a reference technology and CAEC values are determined by the impact on mitigation of implementing that option alone. The solid red bars, where these appear, show the thermodynamic limit for CAEC in cases where this can be defined. In the case of methanol production, this limit is the energy released by combusting methanol, and in DACCS, this limit represents the minimum energy to capture all CO₂ from a gas mixture at 298 K with a concentration of 400 parts per million CO₂ and compress the resulting CO₂ stream to 10 atmospheres (see Methods and SI).

Fig. 6 | Carbon Abatement Energy Cost (CAEC) of different mitigation options. The alternative routes considered for each product or service are listed in Table 1. System boundaries are defined by available LCA or process studies for each route. Individual studies are shown (open circles). Group averages of each mitigation route (red filled circles) were determined by taking the mean of the CAEC values for all available studies. In the case of switching electricity to low-carbon generation technologies, we use adjusted estimates in the literature derived from numerous LCA studies. Please refer to the supplementary information for the full list of references. Thermodynamic limits and all other values are given in terms of the equivalent thermal energy. Mitigation options are classified into four groups: options that are already proven to reduce emissions at Gt-CO₂-eq scale (“proven”), options that could reduce emissions at Gt-CO₂-eq scale in future if deployed today (“potential”), options that have been proposed as able to reduce emissions at Gt-CO₂-eq scale (“proposed”) and options that would not, on grounds of scale, be able to reduce emissions at Gt-CO₂-eq scale (“not possible”), e.g., because demand for these products is too low or because the energy cost of the route would preclude its use at large scale.

227 There are several points that emerge from this figure. Firstly, in comparison to all
228 other options, replacing fossil-fuel power sources with low-carbon electricity is very

attractive in energy cost terms for the purpose of mitigating CO₂-eq. The CAEC of switching to low-carbon electricity has a mean value of 0.046 kWh per kg CO₂-eq mitigated. Secondly, some carbon embedding routes are extremely energy costly, such as the production of methanol and the synthesis of DMC, a process that requires methanol. For instance, in the case of methanol, the thermodynamic limit for CAEC is already quite high (4.58 kWh per kg CO₂-eq) and process inefficiencies further increase this CAEC to a mean value of 10.03 kWh per kg CO₂-eq.

Amongst the carbon removal options DACCS has the highest CAEC, even though this CAEC only includes process energy. For instance, the type of DACCS that we consider in this study uses a significant amount of calcium carbonate pellets, for which industrial limestone must be quarried and processed. Similarly, these studies^{22,30-33} suggest significant use of natural gas for generating heat and electricity for DACCS but the energy and infrastructure to supply natural gas to the DACCS facilities or emissions from methane leakage during delivery are not currently considered in the studies. Regardless of the design choice, such infrastructure and associated material and energy requirements will inevitably increase the overall CAEC and should be accounted for in a technology that is meant to be deployed at global scale.

In contrast to DACCS, BECCS options have a lower CAEC and therefore appear to be favourable among the carbon removal options in terms of energy cost. Even though bioenergy has been reported to have very low EROI compared to other renewable options³⁴, the ability of BECCS to produce electricity or fuel, while also removing atmospheric CO₂, leads to a low CAEC. We note that if the CO₂ mitigation performance of BECCS is calculated for introducing BECCS alone instead of using it to replace a reference technology, the CAEC would formally be negative on account of the net energy assumed to be generated by BECCS. However, if BECCS were used solely for CO₂ removal rather than for energy

generation, the energy generated could not be counted as useful and the CAEC could not be defined. Moreover, BECCS is often considered as both a CO₂ reduction technology and a source of energy. Therefore, we restrict attention to the case where BECCS is deployed as part of the energy system and replaces some other energy source. We compare BECCS options against a reference technology to show the trade-off between investing into a high energy yield low-carbon technology (e.g., fossil-fuel power plants with carbon capture and storage) and a negative-carbon technology that might also result in a net energy yield.

A final remark on Fig. 6 concerns the importance of the scalability of each technology and whether a technology can provide a mitigation potential in the Gt-CO₂-eq scale. Pathways that aim to limit warming to 1.5 °C require annual greenhouse gas emissions per year to be reduced to 25-30 Gt-CO₂-eq by 2030³⁵ while current global CO₂ emissions from fossil fuels and industry lie between 35 and 40 Gt-CO₂-eq². While it is important to make use of any options that could reduce emissions, the technologies that can provide mitigation at Gt-CO₂-eq scale would be the most relevant in limiting or reversing climate change. Of all technologies that we have considered, only switching to low-carbon energy generation already reduces emissions at Gt-CO₂-eq scale on relevant time scales (e.g. 5 years). Hydrogen production using low-carbon alternatives can theoretically provide around 1 Gt-CO₂-eq mitigation since today about 6% of global natural gas and 2% of global coal consumption is used in hydrogen²⁶; this mitigation potential would increase if hydrogen were employed more widely as a fuel. On the other hand, chemical compounds that allow carbon embedding do not have sufficiently large demand to provide meaningful mitigation potential. Methanol is produced globally at Mt scale annually, whereas DMC and polyols are produced only at kt scale²⁰. This point has been recently demonstrated in a wider context for various CO₂ based compounds³⁶. Finally, there are the proposed options of DACCS and BECCS that, according to model results, could provide mitigation at Gt-CO₂-eq scale but have not yet been demonstrated at

scale of more than kt-CO₂ in terms of their CO₂ removal^{37,38}. Whether these options can provide mitigation at scale or not is yet to be tested. It is also relevant that the latest special report by the IPCC on climate change and land³⁹ stresses that large-scale deployment of bioenergy technologies can have a negative impact on food security, land degradation and desertification.

BECCS and DACCS in mitigation analysis

We now focus on BECCS and DACCS in the context of how they are being modelled in IAMs in order to expand on our discussion on the CAEC of negative emission technologies. Fig. 7a shows the range of CAECs for DACCS derived from IAM studies for which we were able to obtain the appropriate data^{3,4}. For DACCS (Fig. 7a), these assumptions fall close to reported process efficiencies but do not consider energy cost of infrastructure and supply chain. These values are likely an underestimation of the energy consumption unless there are significant improvements in the technology and supply chain of DACCS that drive down the energy requirements.

Fig. 7 | Comparison of carbon removal routes along with bioenergy use per carbon dioxide removal modelled in several IAMs. a., CAEC of DACCS as given in Fig. 6 and also as used in IAMs. Two IAMs, MERGE-ETL and WITCH, assume 7.5–8 and 9.9 GJ per tCO₂ removed for DACCS³, respectively. Another IAM, TIAM-Grantham, assumes that 300 EJ/year energy to remove 30 Gt-CO₂ removed per year⁴. **b.,** Bioenergy use per CO₂ removal as assumed by IAMs and as reported by the LCA studies. We plot the ranges in the left column using values from a recent study² that presents an overview of results from 11 IAMs provides CO₂ removal potential by BECCS modelled by those IAMs when their models are constrained by limited biomass supply of 100 EJ. In the middle column, we provide values for BECCS_{power} using the MONET framework⁴⁰. The top and bottom notches on each bar represent the scenarios where the framework targets to remove 1 Gt-CO₂ in each region assuming *high* and *low* biomass yield, carbon intensity of energy sources and chemicals, biomass moisture and processing energy, respectively. The red notch assumes average values instead. In the right column, we calculate the bioenergy use per CO₂ removal using values reported in the BECCS_{fuel} LCA studies⁴¹⁻⁴².

For BECCS, we were only able to compare the LCA studies against the mitigation potential of BECCS expressed as bioenergy use per unit CO₂ removal (Fig. 7b) because there are no data available in the literature to calculate the net energy use per kg-CO₂ removed of BECCS as treated in IAMs, nor to resolve the energy costs of BECCS_{power} and BECCS_{fuel}. Even though IAMs play a critical role in assessing deep decarbonisation scenarios, their modelling details are often not transparent⁴³, and their modelling assumptions for different technology routes are not available to the public in full detail⁴⁴, which makes it difficult to compare their

assumptions and modelling results with available bottom-up modelling studies. In Fig. 7b, most strikingly, we see that the bioenergy use per CO₂ removed assumed by IAMs (left-hand column) either match or underestimate the values in the LCA studies (middle and right-hand columns) some of which do not fully consider land-use change impacts of deploying large scale bioenergy crops. The values reported by these LCA studies should be considered as best-case estimates for BECCS options, where the performance reported within these studies can only be possibly achieved at limited scale (less than 1 Gt-CO₂). On the other hand, IAMs in Fig. 7b assume comparable or lower energy costs for BECCS implemented at significantly larger scales (between 5 and 10 Gt-CO₂ per year). Achieving this low energy cost for such a large scale of CO₂ removal is, at best, a very optimistic assumption that requires further validation. Apart from the risk that CO₂ removal options will never become “energy cheap”, the reliance on large-scale CO₂ removal in the second half of the century may lead to climate policy scenarios that favour weaker emissions reduction targets in the nearer term, and risk missing altogether the opportunity for deep decarbonisation⁴⁵. In the case where CO₂ removal remains as energy costly as described here, CO₂ removal technologies might never get deployed at global scale and global warming might very well exceed 2 °C if current climate policy is mainly based on the assumption of future availability of such services.

Discussion and conclusions

Our analysis using the CAEC metric demonstrates that many yet-to-be deployed mitigation options have a relatively high energy cost compared to existing options such as substituting renewables for fossil fuels in electricity generation. Of particular note are the high energy requirements of methanol and DMC production, and of DACCS. A combination, for example, of direct air capture to make methanol would be a poor idea in energy terms. In contrast, decarbonising electricity with renewables is highly attractive in energy terms and should be prioritised.

When deploying carbon removal technologies, the investment decisions would ultimately depend on the bundle of services required by society and the sustainability of resources such as land and water. BECCS has significant issues both in its resource effectiveness due to its low EROI and in its sustainable scalability while preserving biodiversity and global food security. Alternatively, DACCS could be a favourable choice in a renewable energy-rich but water- and land-constrained world that requires carbon removal as a service. However, that would absolutely require low-carbon energy generation, hence, the priority should be adoption of renewables on a global scale. Wider implementation of renewable generation would also reduce the need for carbon dioxide removal technology to constrain temperature rise within any low-carbon scenario³⁵, and so mitigate the impacts of the associated energy and resource demands.

Hydrogen is a promising route in terms of low CAEC (particularly electrolysis from renewables) and offers long-term storage, heating and transport options that renewables themselves do not provide. Decarbonising hydrogen can theoretically already provide 1 Gt-CO₂ mitigation and could provide larger mitigation potential if its use is more widely adopted as fuel.

While economic considerations such as capital and operating expenditures often drive where resources are usually invested, it is important to know that deploying these mitigation technologies will have an energy cost to our society and we should carefully understand all the energy costs involved in their deployment before any decision around large-scale deployment. If use of a technology is not favourable in energy terms, then that technology should not be considered as a favourable mitigation option.

Methods

Carbon Abatement Energy Cost (CAEC). For processes that use energy to produce a product or service (Fig. 1), CAEC is expressed by the ratio between the net amount of energy consumed, $\Delta E = E_{in} - E_{out}$, per kilogram of CO₂ abated, $\Delta C = CO_2^{in} - CO_2^{out}$,

$$CAEC = \frac{\Delta E}{\Delta C} \quad (1)$$

This relation can be used to evaluate the energy cost of introducing a process, for example a negative emissions technology, or removing a process, which might be the result of measures that reduce energy demand. CAEC can only be determined if CO₂ is abated, that is $\Delta C < 0$ (lower quadrants in Fig. 2b). In some cases, a process or product might require both thermal and electrical energy. In such cases, we convert electrical energy back to thermal energy using a conversion factor depending on the primary fuel stock, e.g. in processes that produce electrical energy using biomass, we use a conversion factor of 26%. All conversion factors are given in the supplementary information. In the case of replacing one source of energy with another source (switching), CAEC is expressed as

$$CAEC = \frac{\Delta E_2 - \Delta E_1}{\Delta C_2 - \Delta C_1} \quad (2)$$

where an energy source #1 is being replaced by another energy source #2. Here, we assume that the amount of energy supplied by source #1. $E_{out,1}$ is replaced with an equal amount of energy from the alternative source, $E_{out,2}$ to satisfy switching, that is $E_{out,1} = E_{out,2}$. Thus, the expression can be written as

$$CAEC = \frac{E_{in,2} - E_{in,1}}{\Delta C_2 - \Delta C_1} \quad (3)$$

The calorific equivalent of the energy required for a process E_{in} can be expressed in terms of *EROI*, which is an indicator of the net primary energy yield E_{out} resulting from each unit of primary energy E_{in} invested in the process: $E_{in} = \frac{E_{out}}{EROI}$. Therefore, the CAEC can be expressed in terms of *EROI*:

$$CAEC = \frac{E_{out}(EROI_2^{-1} - EROI_1^{-1})}{\Delta C_2 - \Delta C_1} \quad (4)$$

First, we characterise a couple of individual processes using existing thermodynamic data to illustrate how CAEC would be determined. At the simplest level of analysis, we calculate the standard enthalpy of a reaction, ΔH , from the difference between the sum of enthalpies of the products and that of the reactants. The CO₂ balance is determined by the quantities involved in the reactions. Whilst this is a simplification of any real process, it is useful to obtain a minimum for the energetic cost of the reaction that no real process can outperform no matter the future technological improvements. In the following thermodynamic analysis of CO₂

conversion, we consider two products: (1) methanol, a fuel and an important component for the chemical industry that can be used as a reactant to produce CO₂-based final products, including polymers, and (2) methane, a key compound for hydrogen production and widely used in the energy and transportation sector.

Today, methanol production is made using synthetic gas, mainly a mixture of hydrogen and carbon monoxide, as a building block to synthesize methanol. Synthetic gas is obtained from carbon feedstock through gasification and results in significant CO₂ emissions that are usually released into the atmosphere. There are low-carbon alternatives to this predominant commercial practice that convert CO₂ into methanol. For example, in one such reaction pathway, CO₂ and low carbon sources of hydrogen (H₂) are converted to carbon monoxide (CO) by the reverse water-gas shift reaction. Later, a mixture of CO, CO₂ and hydrogen are used for the synthesis of methanol.

Thermodynamically, the minimum energy required to form methanol from the ultimate starting compounds of CO₂ and water would be equivalent to the energy consumed in the reverse process to the combustion of methanol.

where ΔH_0 is the standard enthalpy of the reaction and (l), (g) denote liquid or gas phase. Here, a positive enthalpy, $\Delta H_0 > 0$, tells us that energy is required to drive this reaction. Any process that synthesizes methanol from CO₂ would require at least this amount of energy. This energy does not reflect additional energy inputs required for catalyst production, product separation, and process efficiencies. This value therefore provides a conservative minimum energy requirement.

Similarly, CO₂ can be converted to methane. The minimum energy required for this conversion would be equivalent to the energy released by combusting methane.

In practice, the reverse combustion reaction to produce methane or methanol from CO₂ and water is extremely hard to drive, and instead the fuels can be produced by the reaction of hydrogen with CO₂, where the hydrogen has been produced in a separate process. We may now determine CAEC for producing methane and methanol from CO₂. Producing 1 mol of methanol and methane requires 726 kJ and 890 kJ, respectively. We use 44.01 g mol⁻¹ as molar mass for CO₂. The carbon abatement energy costs are then 4.58 kWh and 5.62 kWh per kg CO₂ for methanol and methane production, respectively. In practical applications more energy will, of course, be needed and CAEC will be higher.

Data availability. The data that support the plots within this paper and other findings of this study are available in the Supplementary Information. Other information is available from the corresponding authors on reasonable request.

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Author contributions

J.N. conceived the study. O.B. designed the study and carried out the data collection with contributions from S.C. and J.N. O.B. carried out the analysis with contributions from all co-authors. M.F. provided the scenarios on electricity from biomass with carbon capture and storage. O.B. and J.N. co-wrote the paper. A.G., A.F., A.W.R., and M.F edited the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper

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