Negative-emissions technology portfolios to meet the 1.5 °C target

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ABSTRACT

Our carbon-intensive economy has led to an average temperature rise of 1 °C since pre-industrial times. As a consequence, the world has seen increasing droughts, significant shrinking of the polar ice caps, and steady sea-level rise. To stall these issues' worsening further, we must limit global warming to 1.5 °C. In addition to the economy's decarbonization, this endeavour requires the use of negative-emissions technologies (NETs) that remove the main greenhouse gas, carbon dioxide, from the atmosphere. While techno-economic feasibility alone has driven the definition of negative-emissions solutions, NETs' diverse, far-reaching implications demand a more holistic assessment. Here, we present a comprehensive framework, integrating NETs' critical performance aspects of feasibility, effectiveness, and side impacts, to define the optimal technology mix within realistic outlooks. The resulting technology portfolios provide a useful new benchmark to compare carbon avoidance and removal measures and deliberately choose the best path to solve the climate emergency.

1. Introduction

Large-scale negative-emissions technologies (NETs) are essential for reaching the 1.5 °C climate target, but they are far from an ideal solution (Anderson and Peters, 2016; Rogelj et al., 2018b). Deploying the most promising NETs (Fuss et al., 2018; Holz et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018) at a large scale, if feasible, could represent a heavy burden to ecosystems and the economy (Fuss et al., 2014; Pires, 2019). Low-cost solutions, such as afforestation and reforestation (AR), soil carbon sequestration (SCS), and biochar (BC) may be difficult to implement (Forster et al., 2020; Seddon et al., 2020), and their effect would be vulnerable to disturbances (Fuss et al., 2018); bioenergy with carbon capture and storage (BECCS) could seriously compromise food security and biodiversity (Dooley and Kartha, 2018; Fuss et al., 2014; Kartha and Dooley, 2016), two already pressing sustainable-development challenges; and emerging technologies, such as direct air carbon capture and storage (DACCS), enhanced weathering (EW), and ocean fertilization (OF), may turn out prohibitively expensive (Keith et al., 2018; Smith et al., 2016). Each of the proposed NET options poses a unique set of challenges related to feasibility, effectiveness, and sustainability. Despite the massive expected scale of NET deployment, several times the scale of today's oil industry (Caldecott et al., 2015), there is little discussion about how to approach and determine an ideal NET mix.

Climate stabilization requires both carbon avoidance and carbon removal measures, as even aggressive decarbonization pathways depend on significant levels of negative emissions (Gasser et al., 2015; van Vuuren et al., 2018). Furthermore, rapid emission reductions face major challenges, such as inertia in the energy system, failure to coordinate mitigation targets, and upward trends in emissions from non-CO_2 greenhouse gas sources (Obersteiner et al., 2018). Alarmingly, the global commitments, e.g. the Nationally Determined Contributions, fall well short of the 1.5 °C climate target (Roe et al., 2019).

Proactive NET planning provides a dual value to mitigate the looming carbon budget deficit. First, by removing carbon dioxide (the main greenhouse gas) from the atmosphere, NETs tackle the root of climate change: excessive greenhouse gas concentrations. Geo-engineering methods, such as solar radiation management (SRM), could be ineffective because they do not reduce greenhouse gas concentrations, and they could be much riskier because their impacts are highly uncertain (Fuss et al., 2018). Hence, while research bodies acknowledge that NETs can play a useful mitigation role, SRM methods should rather only be considered as a last resort (Shepherd, 2009). Second, timely NET deployment can help ensure that climate targets are reached safely and sustainably, avoiding a temperature overshoot, stranded assets, and backstop reliance (Obersteiner et al., 2018) late in the century, as mitigation pathways imply (Anderson and Peters, 2016; Köberle, 2019; Rogelj et al., 2018b).

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In this study, we develop and implement a prioritization framework that assesses NETs' critical performance aspects of feasibility, climate change mitigation effectiveness, and side impacts (Fig. 1) (Fuss et al., 2018; Kartha and Dooley, 2016; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018; Shepherd, 2009). The comprehensive set of criteria extends well beyond techno-economic feasibility, which is usually the only aspect considered (Forster et al., 2020; van Vuuren et al., 2017). The framework integrates recent established assessments (Fuss et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018; Shepherd, 2009) of the most promising NETs (Fuss et al., 2018; Holz et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018) to determine optimal technology portfolios according to different preferences. As a result, we estimate more diversified technology portfolios than past NET solutions, which usually only consider BECCS and forestry and other land use (Rogelj et al., 2018b). As Hilaire et al. (2019) explain, recent studies, such as Chen and Tavoni (2013), Holz et al. (2018), Marcucci et al. (2017), and Strefler et al. (2015, 2018)), are increasingly considering other NETs in climate mitigation models. Our framework builds on some of their findings, and additionally presents a systematic assessment of NETs. Moreover, building also on estimates of NETs' achievable potential, which are well below biophysical limits (Fuss et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018; Shepherd, 2009; Stocker et al., 2013), we calculate the actual deployment level of the most promising NETs that would be necessary to meet the 1.5 °C target under three different scenarios (Rogelj et al., 2018b).

2. Methods

We present a framework (Fig. 2) based on a typical multi-criteria decision analysis (MCDA) process employed in sustainable energy (Wang et al., 2009). MCDA's goal is to evaluate and rank NETs' balanced performance, and the framework's final output consists in defining the most promising NET mix to deliver the negative emissions needed to achieve the 1.5 °C climate target. The selection of NET alternatives, the definition of performance categories, and the performance evaluation are based on the consensus expressed in recent, comprehensive literature reviews (Fuss et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018; Shepherd, 2009).

The seven promising NETs evaluated are: afforestation and reforestation (AR), biochar (BC), bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), enhanced weathering on land and in oceans (EW), ocean fertilization (OF), and soil carbon sequestration (SCS) (Fuss et al., 2018; Holz et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018).

Our framework analyses NETs' key attributes and integrates their evaluation. We grouped the key attributes into three areas: feasibility, side impacts, and climate change effectiveness, with the aim of providing a comprehensive, yet easy to understand evaluation of NETs' overall performance. The evaluation criteria are mostly based on ordinal data. For the qualitative criteria assessed, we consider only the consensus from expert groups; we clearly explain the aspects evaluated (section 2.1 and Supplementary Information); and we use a sound, intuitive scale for their quantification, such as IPCC's level of confidence scale (Manning, 2006).

Among the three performance areas, previously proposed NET portfolios consider only hard factors within feasibility, namely techno-economic feasibility (Forster et al., 2020; Nemet et al., 2018; van

Vuuren et al., 2017). In our framework, feasibility includes both hard and soft factors. Given the crucial importance of soft factors, like governance and public acceptance (both evaluated under governance), their assessment is essential to understand each technology's likelihood of implementation (Bellamy, 2018; Forster et al., 2020; Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018). Climate change effectiveness addresses NETs' ability to mitigate climate change. Despite the consensus on crucial effectiveness aspects of NETs and the enormous gap in performance among the options, effectiveness has not been weighed in as a consideration to define NET portfolios in the past. Side impacts cover environmental, social, and economic aspects. Large-scale NET deployment involves diverse far-reaching effects, besides the intended climate change mitigation (Smith et al., 2016). While assessing side impacts entails separate in-depth studies for each technology, the scale that we defined reflects the consensus on the expected scale of the impacts (Fuss et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018; Shepherd, 2009).

2.1. Performance evaluation

Through the evaluation framework that we propose, our goal is to integrate the scientific consensus on the performance of NETs' key attributes (Fuss et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018; Shepherd, 2009). Uncertainties remain among several NET aspects, but the consensus around the relative performance level of NETs' critical aspects is evident enough to already get valuable insights from their joint evaluation. Most importantly, the urgency and scale of the climate crisis call for an open discussion around NET portfolios with a broad perspective as soon as possible (van Vuuren et al., 2017).

The three performance areas provide a brief, quantitative summary of NETs' key implications. More precisely, feasibility evaluates the viability of NETs. It assesses NETs' technology readiness level (TRL) level (Royal Society and Royal Academy of Engineering, 2018), the probability of cost-effectiveness (Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018), and "public principles of good governance" (Bellamy, 2018). Climate change effectiveness reflects NETs' mitigation effectiveness once implemented. Effect mainly evaluates CO_2 capture effectiveness (Shepherd, 2009); permanence assesses NETs' storage time (Scott et al., 2015); and timeliness evaluates NETs' flexibility and speed of effect, once technologies become available at scale. Side impacts reflect NETs' environmental, economic, and social effects, besides climate change mitigation (already considered under effectiveness) and technologies' affordability (already considered under economic feasibility). Their evaluation accounts for both positive and negative impacts, where the mid-point represents neutral impacts. For consistency, qualitative, ordinal data (except for TRL) are in line with IPCC's level of confidence scale (Manning, 2006) (Supplementary Information).

To minimize the influence of the authors' judgement, the performance evaluation of the nine categories follows clear criteria (Table 1), some of which have been used in separate studies to assess NETs' diverse aspects. For comparability among the criteria, all evaluations are normalized to a common scale from 0 to 10 (i.e., absolute normalization). The Supplementary Information provides the detailed assessment of all NETs.
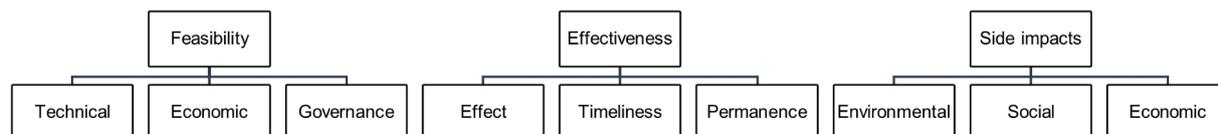
Fig. 1. Category breakdown for prioritization framework.
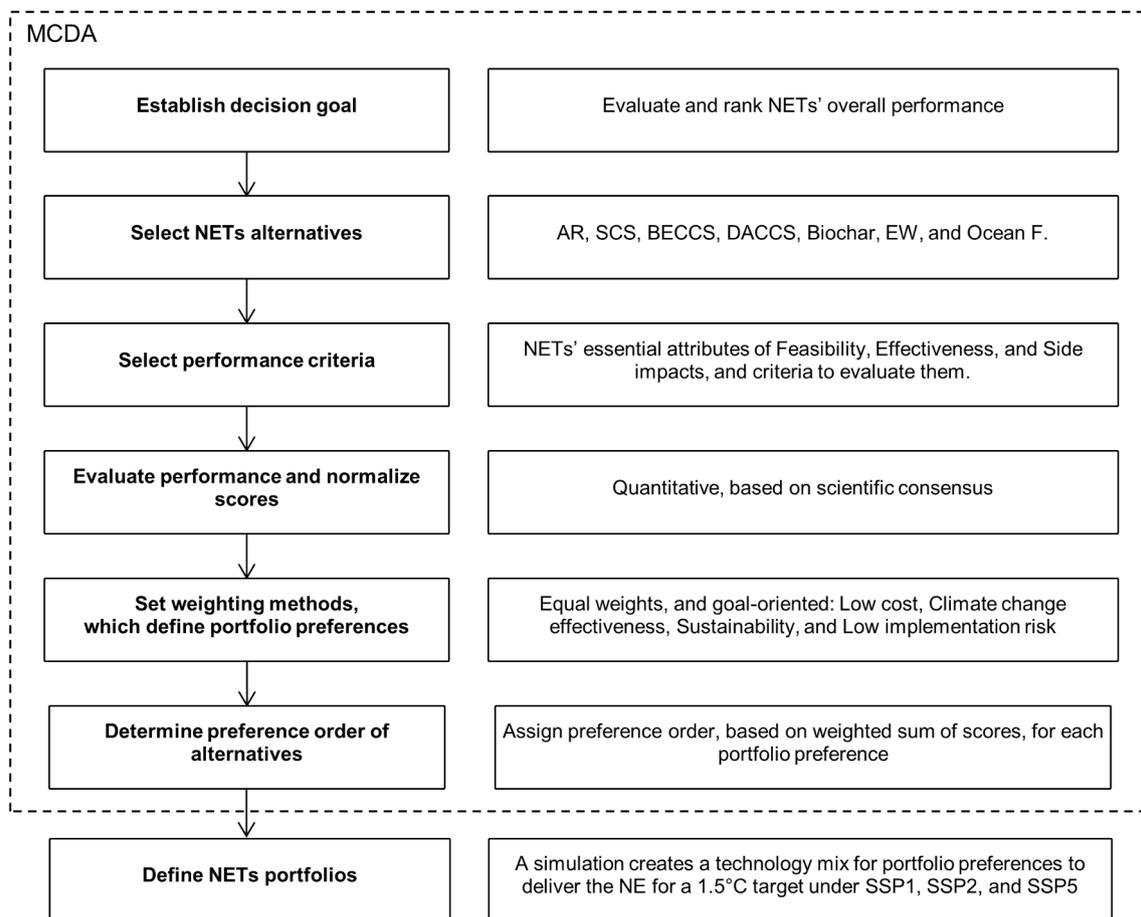
Fig. 2. Framework to define NET portfolios.

2.2. Creation of portfolio preferences

After calculating each NET's performance in the nine categories, we assigned weights to each category to estimate overall performance. Through a weighted sum (the most common approach in MCDA for sustainable energy), each technology gets a final score and a rank (Wang et al., 2009). We created seven different weighting alternatives, each representing a portfolio preference, to analyze how different preferences would affect the technology selection (Table 2).

Equal weights (EQ) is the most common weighting method for decision-making on sustainable energy; it requires minimal knowledge of stakeholder preferences; and its results are often almost as good as optimal weighting methods (Wang et al., 2009). Besides, we defined six additional portfolio preferences with a dual purpose: they present alternative scenarios on how stakeholder preferences could affect technology selection, and they provide a useful stress test of how different weightings can affect the results. Portfolios can prioritize cost, climate change effectiveness, or side impacts. Additionally, each priority has a low-risk variant to more heavily weight feasibility. The portfolio Economy (EC) reflects the traditional focus on cost (van Vuuren et al., 2017). Climate change (CC) emphasizes effectiveness to mitigate climate change, NETs' ultimate goal. Sustainability (SU) sets up a NET portfolio with the most benign side impacts. The low-risk variants (EC_lr, CC_lr, and SU_lr) shed light on how the portfolio mix could change if we incorporate risk, which is crucial for portfolio optimization in all areas, from the finance to the energy sector. In our context, low risk refers to adoption risk, which we consider by assigning heavier weights to the feasibility categories, as shown in Table 2.

2.3. Simulation

2.3.1. Background

We defined a simple simulation model to determine the ideal NET portfolio mix when comprehensively evaluating their performance. The simulation model (Fig. 3) defines the optimal NET mix for diverse portfolio preferences and negative emissions required. The model integrates the scientific consensus on NET performance (Fuss et al., 2018; Minx et al., 2018; Shepherd, 2009) (section 2.1) and reasonably expected NET potentials (Fuss et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018) (section 2.3.3) to fulfill different expected levels of negative emissions (section 2.3.2). Its output outlines technology deployment pathways for 2020–2100 to achieve the 1.5 °C climate target.

2.3.2. Negative-Emissions need

Reaching the 1.5 °C climate target requires large-scale NET deployment, likely ranging from 150 to 1180 $GtCO_2$ throughout the 21st century (Minx et al., 2018; Rogelj et al., 2018b). In our study, we evaluated three different levels of negative emissions along that range. To put the NET deployment scale in context, we considered three negative-emissions need levels (Table S8) in line with shared socio-economic pathways (SSPs) (Rogelj et al., 2018b). SSP2, with a medium demand for negative emissions (620 $GtCO_2$), is the study's primary focus. As it follows moderate assumptions for future developments (Fricko et al., 2017), SSP2 is often the reference point among other scenarios. SSP1 requires the lowest negative emissions (400 $GtCO_2$). Its optimistic storyline assumes lower emissions from low energy demand. In contrast, SSP5 requires the highest negative emissions (1180 $GtCO_2$) due to high energy demand and a strong preference for fossil fuels (Rogelj et al.,

Table 1
Overview of evaluation of all performance aspects.

Aspect	Evaluation	Sources	Scale [units]	Normalized score
Technical feasibility	Ordinal data, based on the technology readiness level (TRL)	Evaluation in review (Royal Society and Royal Academy of Engineering, 2018)	0–9 [-]	0–10, (TRL/9)·10
Economic feasibility	Continuous data, based on NETs' costs and carbon price under a 1.5 °C climate policy	NETs' costs from reviews (Fuss et al., 2018; Minx et al., 2018) and carbon price in review (Nemet et al., 2018)	0–100 [%]	0–10 [IPCC's confidence scale] (Manning, 2006)
Governance feasibility	Ordinal data, following framework (Bellamy, 2018): "Public principles for the good governance of NETs"	Inputs from reference (Bellamy, 2018) and reviews (Fuss et al., 2018; McLaren, 2012; Minx et al., 2018; Shepherd, 2009)	"Very low" to "very high"	0–10 [in line with IPCC's scale]
Mitigation effect	Ordinal data	Based on evaluation done in review (Shepherd, 2009)	"Very low" to "very high"	0–10 [in line with IPCC's scale]
Timeliness	Ordinal data, based on (1) time to reach max. capture capacity and (2) other factors (flexibility, controllability, reversibility)	Authors' assessment, based on reviews (Fuss et al., 2018; Minx et al., 2018)	"Very low" to "very high"	0–10 [in line with IPCC's scale]
Permanence	Ordinal data, "Temporary" / "Permanent", based on storage time	Storage time estimates and classification in reference (Scott et al., 2015)	"Very low" to "very high"	0–10 [in line with IPCC's scale]
Environmental impacts Economic impacts Social impacts	Ordinal data	Summary of conclusions in reviews (Fuss et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018; Shepherd, 2009)	"Highly negative" to "highly positive" (7 levels)	min–max scaling

2018a). The Supplementary Information provides more details on the SSPs and the climate policies behind the estimates of cumulative negative emissions.

2.3.3. NET potential

The simulation uses realistic estimates of NET potential. From biophysical limits to reasonable scaling-up constraints, researchers have continuously narrowed the ranges of expected potential. In our study, we use recent estimates of potentials only from scientific publications that involve expert consensus, and whose estimates are well below the NETs' biophysical limits (Fuss et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018; Shepherd, 2009; Stocker et al., 2013). As researchers from those publications conclude that ocean fertilization's potential is highly uncertain, we exclude it and only provide estimates for the other options. Table 3 shows the main parameters to define NETs' constraints on cumulative and scaling-up potential throughout 2020–2100.

Since the cumulative potential and the specific yearly potentials (potential in 2050 and peak potential) in Table 3 were defined independently, we set as the ultimate constraint the most limiting estimate. More specifically, the maximum cumulative potential will be the smallest value between the cumulative potential from the literature (highest value from the range in Table 3), and the resulting cumulative potential of each NET curve (Fig. 4). We built such curves with the inputs in Table 3: start time, time to peak, potential in 2050, and peak potential. If the potential peaks until 2050, the flux increases linearly from zero in the start year to the peak potential. If the potential peaks after 2050, the flux grows linearly from zero in the start year to the 2050 potential, and then from the 2050 potential to the peak potential. Again, since the range of potentials in 2050 and at the peak (Table 3) already represent reasonable limits well below NETs' biophysical potential (Fuss et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018; Shepherd, 2009; Stocker et al., 2013), we took the highest value as the constraint for the curves. Within such constraints on NETs' cumulative potential and expected scale for 2020–2100, the actual deployment level of each option was determined by the amount of negative emissions needed, the attractiveness under each portfolio preference, and the simulation's deployment settings (Table S9).

Land use and geological storage, resources for which more than one alternative could compete, do not seem to constrain NETs' aggregated potential. Since we heavily constrained BECCS potential, as indicated in Table 3, BECCS's and AR's land requirements do not directly compete with each other. For BECCS, we consider the use of highly productive crops grown on existing arable land (Royal Society and Royal Academy of Engineering, 2018), which is key to quickly reach emissions break-even; for AR, whose priority would be reforestation, any additional land requirement would be only marginal land (Fuss et al., 2018). In contrast, BECCS and DACCS could compete for the same geological storage potential. However, it is unlikely that geological storage could become an important constraint at the scales considered for BECCS and DACCS. Even deploying the full potential of both, 633 GtCO$_2$ (BECCS's 300 and DACCS's 333 GtCO$_2$), could be feasible, given a global storage capacity of 3360 GtCO$_2$ (20% of the global theoretical capacity) (Royal Society and Royal Academy of Engineering, 2018). In the portfolios proposed, BECCS's and DACCS's largest combined deployment is lower than 500 GtCO$_2$ for the worst case (SSP5); for a medium negative emissions need (e.g., SSP2), the portfolio with the largest amount of DACCS and BECCS together results in less than 300 GtCO$_2$ from both NETs. Furthermore, DACCS's co-location flexibility would facilitate accessing available storage sites (Fuss et al., 2018), which would reduce the competition for sites with BECCS.

2.3.4. Ranking of NETs by portfolio preference

The simulation ranks NETs based on their performance. Through the weighted sum method, as introduced in section 2.2, it evaluates the performance of each NET under all seven portfolio preferences. The two inputs for the weighted sum are the results of NETs' evaluation (Table S7) and the portfolio weights (Table 2). We then obtain a performance score and a ranking of technologies for each portfolio preference. The ranking indicates the priority order to deploy each NET, and we deploy as many options as needed, until fulfilling the demand for negative emissions.

2.3.5. NET deployment

While climate mitigation scenarios typically assume large NET

Table 2

Weights for portfolio preferences. The bold values indicate the highest weighted metrics.

Portfolios	Considerations	Feasibility (related to risk before implementation)			Climate change effectiveness (once implemented)			Side impacts (besides climate change mitigation)		
		Technical	Economic	Govern.	Effect	Time.	Perm.	Environ.	Econ.	Social
Equal weights	33% each: feasibility, climate change effectiveness, and side impacts	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111
Economy	90% economic feasibility	0.013	**0.900**	0.013	0.013	0.013	0.013	0.013	0.013	0.013
Economy, low risk	45% economic feasibility, 90% overall feasibility	**0.225**	**0.450**	**0.225**	0.017	0.017	0.017	0.017	0.017	0.017
Climate change effectiveness	90% climate change effectiveness	0.017	0.017	0.017	**0.300**	**0.300**	**0.300**	0.017	0.017	0.017
Climate change effectiveness, low risk	45% climate change effectiveness, 45% feasibility	**0.150**	**0.150**	**0.150**	**0.150**	**0.150**	**0.150**	0.033	0.033	0.033
Sustainability	90% side impacts	0.017	0.017	0.017	0.017	0.017	0.017	**0.300**	**0.300**	**0.300**
Sustainability, low risk	45% side impacts, 45% feasibility	**0.150**	**0.150**	**0.150**	0.033	0.033	0.033	**0.150**	**0.150**	**0.150**
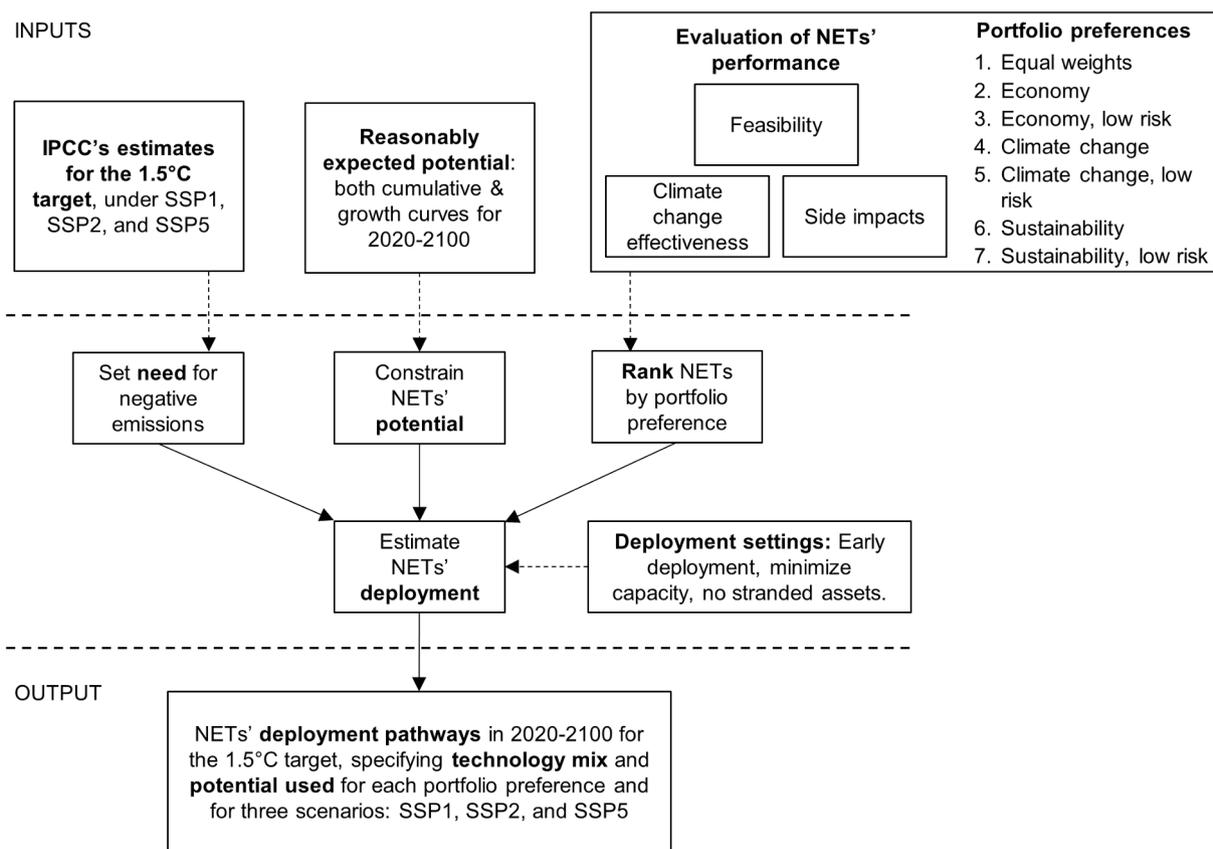
Fig. 3. Schematic view of the simulation model's main modules.

deployment late in the century (Bednar et al., 2019), we present a more cautious alternative. Delaying NET deployment poses large risks related to temperature overshoot, stranded assets, and backstop reliance (Obersteiner et al., 2018). Therefore, timely NET deployment is essential to effectively harvest the main benefits of NETs: first and foremost, hedging risk, and second, reducing climate change mitigation costs (Bednar et al., 2019).

In our simulation, we avoid stranded assets, minimize installed capacity, and prioritize early deployment to reduce the likelihood of a temperature overshoot and backstop reliance (Table S9). Like Obersteiner et al. (2018), we aim to provide a timely NET deployment strategy. However, we present a broader set of NET alternatives, to be deployed following specific portfolio preferences. Moreover, we assess larger amounts of negative emissions, 400, 620, and 1180 GtCO$_2$, which

are expected to be needed under SSP1, SSP2, and SSP5 (Rogelj et al., 2018b), as opposed to the low exceedance budget that they considered of 232 GtCO$_2$ (Obersteiner et al., 2018). The Supplementary Information provides further details on the deployment settings.

3. Results and discussion

3.1. NET performance

NET performance widely varies among critical aspects (Fig. 5). With an average of 53%, NETs' coefficient of variation (CV) across the nine categories ranges from 28% (DACCS) to 76% (OF) (Table S7). Within performance areas, climate change effectiveness clearly distinguishes effective from ineffective measures. The strong correlations among

Table 3
Parameters for NET potential.

NET option	Cumulative potential 2020–2100 [GtCO$_2$]	Start time [Year]	Time to peak [Years]	Potential in 2050 [GtCO$_2$/yr]	Peak potential [GtCO$_2$/yr]	Saturation/Lifetime[a] [Years]
AR	100–300 (Royal Society and Royal Academy of Engineering, 2018)	2020	20[c] (Houghton et al., 2015)	0.5–3.6 (Fuss et al., 2018; Minx et al., 2018)	0.5–3.6 (Fuss et al., 2018; Minx et al., 2018)	80 (Houghton et al., 2015)
BC	100–200 (Royal Society and Royal Academy of Engineering, 2018)	2020	30 (Holz et al., 2018)	0.5–2 (Fuss et al., 2018; Minx et al., 2018)	0.5–2 (Holz et al., 2018)	>100 (Fuss et al., 2018; Scott et al., 2015)
BECCS	300-350[b] (Fuss et al., 2018; Holz et al., 2018; Minx et al., 2018; Royal Society and Royal Academy of Engineering, 2018)	2020	30[d] (Fajardy and Mac Dowell, 2017; Holz et al., 2018)	0.5–5 (Fuss et al., 2018; Minx et al., 2018)	0.5–5 (Holz et al., 2018)	50 (Fajardy and Mac Dowell, 2018)
DACCS	200–500 (Royal Society and Royal Academy of Engineering, 2018)	2035	70 (Holz et al., 2018)	0.5–5 (Fuss et al., 2018; Minx et al., 2018)	0.7–7 (Holz et al., 2018)	30 (Fasihi et al., 2019)
EW	100 (Royal Society and Royal Academy of Engineering, 2018)	2038	70 (Holz et al., 2018)	2–4 (Fuss et al., 2018; Minx et al., 2018)	2.5–5 (Holz et al., 2018)	>100 (Fuss et al., 2018; Scott et al., 2015)
SCS	20–100 (Royal Society and Royal Academy of Engineering, 2018)	2020	30 (Holz et al., 2018)	2–5 (Fuss et al., 2018; Minx et al., 2018)	2–5 (Fuss et al., 2018; Minx et al., 2018)	20 (IPCC et al., 2006)

[a] Saturation/lifetime refers to the time during which NETs will capture CO$_2$, once capacity is installed. We report saturation time for AR, BC, EW, and SCS, and lifetime of infrastructure for BECCS and DACCS.

[b] 300 GtCO$_2$ according to reference (Royal Society and Royal Academy of Engineering, 2018), and 350 GtCO$_2$ according to cumulative potential from curves based on (Fuss et al., 2018; Holz et al., 2018).

[c] Assuming 10 years for installation of all AR capacity, and 10 years to reach peak sequestration potential (Houghton et al., 2015).

[d] For BECCS, the time to reach maximum installed capacity is 20 years (Holz et al., 2018), and we assume 10 years to breakeven (time to start achieving net negative emissions), as estimated for cropland (including indirect land use change) (Fajardy and Mac Dowell, 2017).

mitigation effect, permanence, and timeliness (Pearson correlations between 0.74 and 0.87, Fig. S5) contribute to widening the effectiveness gap. Feasibility scores show that techno-economically feasible NETs are not necessarily easier to implement, since technical and economic feasibility strongly correlate between them (0.61) but weakly with governance (0.21 and 0.18). High governance barriers (low governance scores) particularly hinder the feasibility of the most techno-economically viable NETs: AR and SCS. Across performance areas, the top three options with the most favourable side impacts (SCS, AR, and BC) are among the bottom four in climate change mitigation effectiveness (and vice versa), mainly due to the strong negative correlation between environmental side impacts and permanence of storage (−0.62). Surprisingly, environmental side impacts strongly correlate with economic feasibility (0.79), which means that the cheapest options also offer the most favourable environmental impacts. In general, NET performance most starkly diverges for climate change effectiveness, the area with the largest variation (average CV of 77%), followed by side impacts (average CV of 44%). More specifically, NET performance exhibits the largest variation for permanence of storage, timeliness, and environmental side impacts (CVs of 90, 85, and 70%). Economic feasibility, usually considered the main decision criterion for technology selection (van Vuuren et al., 2017), is less critical. It resulted in the lowest variation (CV of 12%) because, under a climate policy that limits warming to 1.5 °C with a low overshoot likelihood, most NETs are estimated to be cost-effective relative to the carbon price at the scale required (Nemet et al., 2018) (Supplementary Information).

If all aspects are equally valued (i.e., adopting an "equal weights" (EQ) portfolio preference), DACCS emerges as the most attractive alternative (score of 7.4), followed by SCS (6.0), EW (5.9), BECCS (5.7), AR (5.3), BC (5.0), and OC (3.0). DACCS's top score results from its high climate change effectiveness (the performance area with the highest variation), overall high feasibility, and low negative side impacts. To realize DACCS's high performance prospects, renewables have to supply its substantial energy requirements (Fuss et al., 2018; Smith et al., 2016), maximizing thereby the carbon captured and avoided. Upon achieving technical maturity, DACCS can deliver exceptional timeliness to further lower the risk of insufficient mitigation efforts. For instance, given its speed of effect, flexibility of co-location (Minx et al., 2018), and

vast potential (seemingly unconstrained by biophysical limits as the other NETs (Fuss et al., 2018)), DACCS can serve as a buffer and a reliable backstop (more reliable than BECCS, as commonly assumed (Köberle, 2019)), if required. SCS stands out for its high positive side impacts and techno-economic feasibility. Notwithstanding its low effectiveness to mitigate climate change and high governance barriers, which may complicate implementation, SCS benefits make it an attractive alternative. More broadly, timeliness and permanence decisively provided the engineered solutions of DACCS, EW, and BECCS an edge over BC and AR, despite BC's and AR's more favourable side impacts (especially environmental). Ocean fertilization (OF) is clearly the worst alternative. We excluded it from all portfolios because, besides its low performance in all three areas, OF potential remains highly uncertain (Fuss et al., 2018; Williamson et al., 2012). If it proves effective at all, its governance challenges (Bellamy, 2018) (reflected in our assessment) could render it infeasible. Hence, we see ocean fertilization at this point as a last resort with a similar risk profile to that of SRM.

3.2. NET portfolios

NETs' early deployment settings result in portfolios that offer the risk-hedging potential that NETs are meant to deliver. The total NET deployment (Fig. 6) peaks at around 2050, and decreases to zero or close to zero in 2100 for most technologies (except for BC and EW, which saturate after 2100). While such adoption rate of NETs could be economically feasible under a 1.5 °C climate policy, as Nemet et al. (2018) suggest in their summary of carbon price assessments, more in-depth economic analyses are needed, which integrate the modelling of all the NETs that we consider. NETs' wide implications for the economy require their integral modelling in mitigation scenarios. DACCS and BECCS, particularly, would have a substantial impact on energy systems (Creutzig et al., 2019).

Due to the large variation in performance across diverse aspects, the optimal NET mix depends on stakeholder preferences. The only exception is SSP5, since its massive negative-emissions need requires virtually the full reasonable potential of all options (Fig. 7c and Fig. 8c) without stranded assets from DACCS and BECCS. In contrast, a mix of two or three technologies would suffice to deliver SSP1's negative emissions
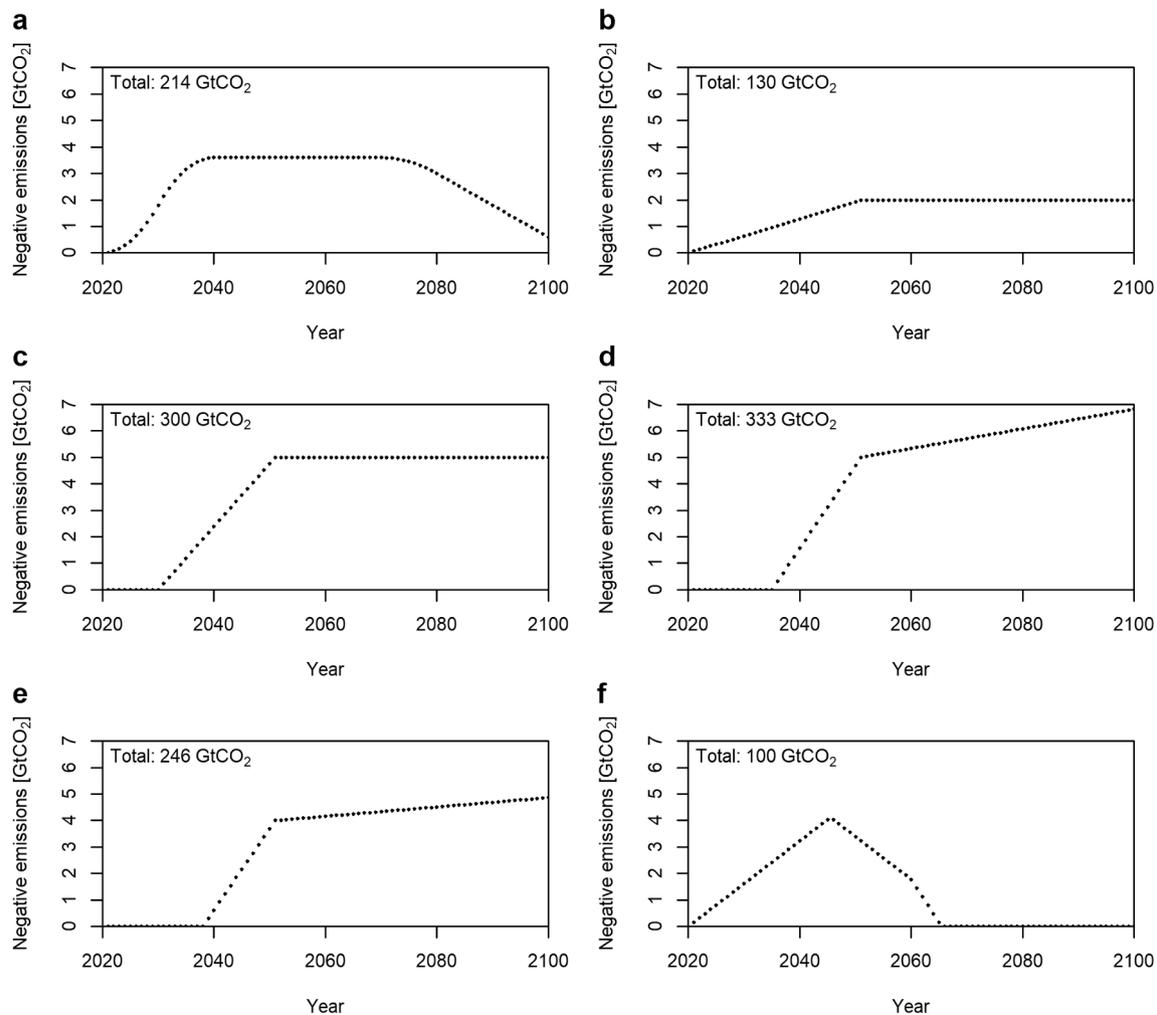
Fig. 4. NET curves of potential for 2020–2100. The points represent the maximum potential of NETs, each year, at the fastest adoption growth that we have considered, based on the input data shown in Table 3. a) Afforestation and reforestation (AR), b) biochar (BC), c) bioenergy with carbon capture and storage (BECCS), d) direct air carbon capture and storage (DACCS), e) enhanced weathering on land and in oceans (EW), and f) soil carbon sequestration (SCS).

(Fig. 7a and Fig. 8a). For a middle-of-the-road scenario, SSP2 (Fig. 7b and Fig. 8b), a cost-minimizing portfolio (EC, Fig. 6b) would prioritize the land-based solutions of SCS, AF, and BC, followed by EW. If stakeholders prioritize climate change mitigation effectiveness (CC, Fig. 6d, e), the engineering solutions of DACCS, EW, and BECCS completely substitute the most economical options. When considering sustainability more broadly (SU, Fig. 6f, g), BECCS's role nullifies because the combination of SCS, AF, BC, and DACCS results in the highest net positive side impacts and suffices to supply SSP2′s negative emissions need. Finally, despite its presumably uncertain techno-economic feasibility (Realmonte et al., 2019), DACCS turns out to be part of all portfolios that minimize risk (EC_lr, CC_lr, and SU_lr, Fig. 6c, e, g), mainly thanks to its high governance feasibility.

3.3. Performance of portfolios

All NET portfolios entail compromises among performance areas, especially between effectiveness and side impacts. The aggregated performance of portfolios' mix provides a glimpse of such compromises (Table 4). Under portfolios EQ, CC, and CC_lr, environmental impacts perform the worst among all categories. For SSP2, EQ includes only a small share of the option with the worst environmental performance (BECCS, with 46 $GtCO_2$) but entails a large deployment of DACCS (229 $GtCO_2$) and EW (246 $GtCO_2$), whose overall environmental performance is still negative due to their material requirements. Compared to SSP1,

EQ`s negative environmental impact more than doubles under SSP2 (260% increase), and triples under SSP5 (Table S12). Hence, reducing negative-emissions dependence (e.g., under SSP1) is crucial to minimize burden-shifting from climate change to other environmental issues. Under SSP2, other portfolios (SU, SU_lr, EC, and EC_lr) can improve EQ's environmental performance, but only at the expense of effectiveness (Table 4). Under SSP5, large negative environmental impacts (mainly from BECCS, DACCS, and EW) ensue the massive negative-emissions need. Furthermore, since it requires NETs' full potential, SSP5 would seriously compromise effectiveness and feasibility due to the dependence on ineffective NETs (AR, SCS, and BC), which pose major governance challenges.

When looking beyond costs (i.e., excluding EC), DACCS emerges as an essential technology to reach the 1.5 °C target. Its remarkable effectiveness to mitigate climate change and superior governance feasibility decidedly position it at the centre of NET portfolios (Fig. 7). SCS is attractive, but mostly thanks to its side impacts and not its potential to mitigate climate change. By helping improve agricultural production and resilience (Fuss et al., 2018), SCS can result in net negative costs, benefiting smallholder farmers in developing countries through increased employment and reduced poverty (Lipper, 2012). EW holds the potential to become a highly effective alternative if it proves technically feasible, and its environmental impacts, justifiable (Bach et al., 2019; Shepherd, 2009). BECCS, usually at the centre stage of 1.5 °C climate scenarios, takes a secondary role, if needed at all. While it can
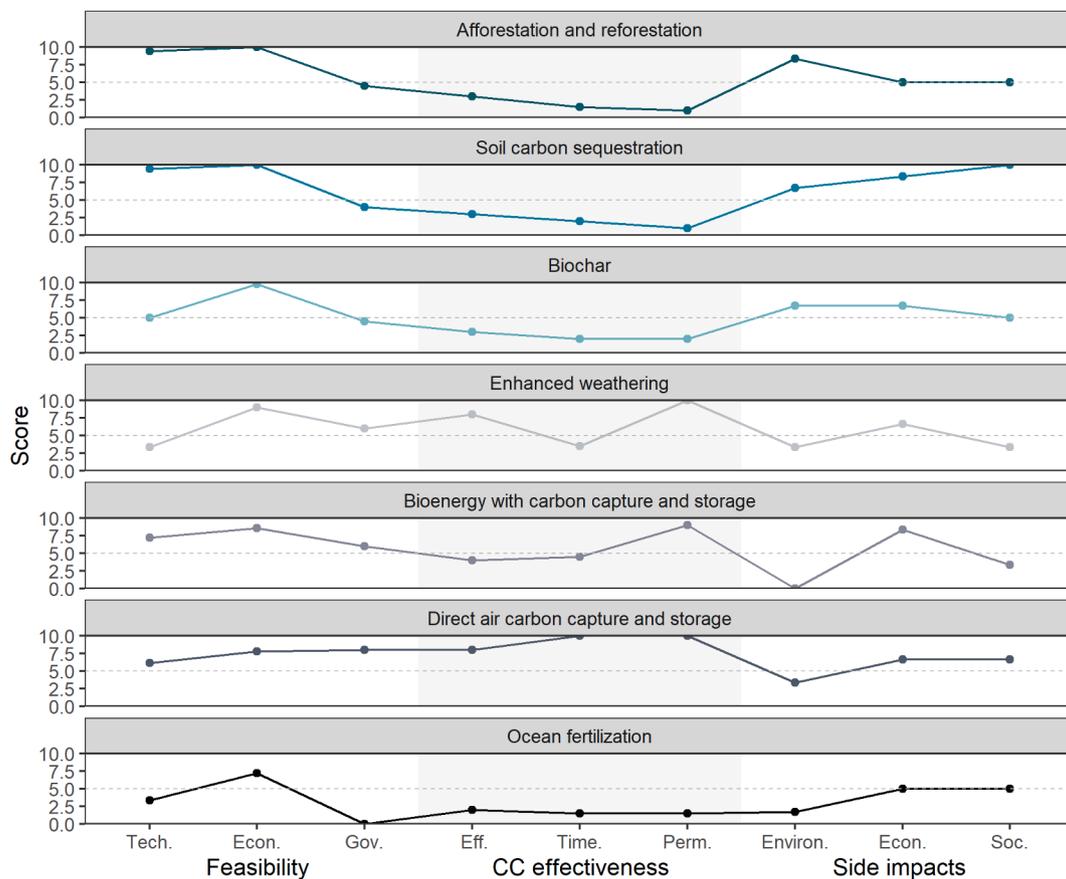
Fig. 5. NET performance. Aspects evaluated: feasibility (technical, economic, and governance-related), climate change effectiveness (mitigation effect, timeliness, and permanence), and side impacts (environmental, economic, and social). Green lines represent natural solutions; grey lines, engineered solutions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

well complement a highly effective (CC and CC_lr) portfolio mix (together with DACCS and EW, under SSP2, Fig. 7b), its social and environmental impacts undermine its climate change mitigation value. To effectively unleash its climate change mitigation potential, BECCS would require the use of highly productive crops grown on existing arable land (Royal Society and Royal Academy of Engineering, 2018), which would further stress food security. Otherwise, if it replaces forests, for instance, the direct and indirect land-use change impacts would render BECCS highly ineffective because it would require unreasonably long periods to become net negative (Fajardy et al., 2019). Besides, the biodiversity loss that can result from potential indirect land-use change would heavily add to the environmental impacts from BECCS's fertilizer and water use (Creutzig, 2016; Fuss et al., 2018). AR, particularly reforestation (Alderton, 2020; Bastin et al., 2019; Lewis et al., 2019), holds a large potential to sustainably mitigate climate change at a low cost (EC and SU, Fig. 7a, b). However, AR's mitigation effectiveness is the worst due to its untimeliness and transient storage ability: it takes several decades for AR to reach its peak potential, and its effect is temporary (Fuss et al., 2018; Haszeldine et al., 2018) and vulnerable to disturbance (Fuss et al., 2018; Haszeldine et al., 2018). After AR, and if it proves technically feasible, BC could complement a cost-optimizing portfolio or one minimizing side impacts (EC and SU, Fig. 7a, b).

The evaluation and ranking of NETs shed light on critical uncertainties. If the need for NETs is high (e.g., close to SSP5's negative-emissions need), all or most of the uncertainties identified in past research (Board, 2019; Minx et al., 2018) would be critical. For the low and medium negative-emissions need (i.e., for SSP1 and SSP2), understanding specific areas will help to decide among the most promising alternatives. EW's high performance in climate change mitigation effectiveness grants more research efforts to clarify its still high

uncertainties around technical feasibility, costs, and environmental impacts (Bach et al., 2019). In-depth cost-benefit analyses could clarify its economic feasibility, and field studies can help understand its potential in a wide range of conditions as well as its environmental impacts (Fuss et al., 2018; Royal Society and Royal Academy of Engineering, 2018). Given DACCS's superior overall performance and large-scale potential, clarifying its environmental impacts (e.g., through prospective life cycle assessments (van der Giesen et al., 2017)) becomes crucial.

3.4. Trade-offs among performance categories

The trade-off between climate change effectiveness and environmental side impacts can help to guide the planning of sound NET strategies. Effective NETs are those engineering solutions (DACCS, EW, and BECCS) capable of "permanently" (>100,000 years) and securely containing the CO_2 captured. Ineffective NETs, those solutions enhancing the natural carbon cycle (SCS, AR, and BC), offer only a "temporary" solution (storing the CO_2 during <1000 years), which simply postpones the problem (Scott et al., 2015). Nonetheless, the low costs and net positive side impacts of ineffective NETs, particularly SCS and AR, make them possible, attractive transition solutions. In some cases, their side impacts alone, SCS's socioeconomic benefits and AR's improvement of biodiversity and ecosystem services, could justify their adoption. To mitigate their effectiveness drawbacks, they need to be implemented as soon as possible. AR timing is especially pressing for a 1.5 °C target by 2100. Considering IPCC's and others' estimate of 80 years to reach its saturation point (Houghton et al., 2015; Nabuurs et al., 2007), every year of delay after 2020 results in an increasing loss of carbon sequestration potential. Gradually installing AR's full capacity by 2030 (during the next ten years) could still harness above 90% of AR potential by
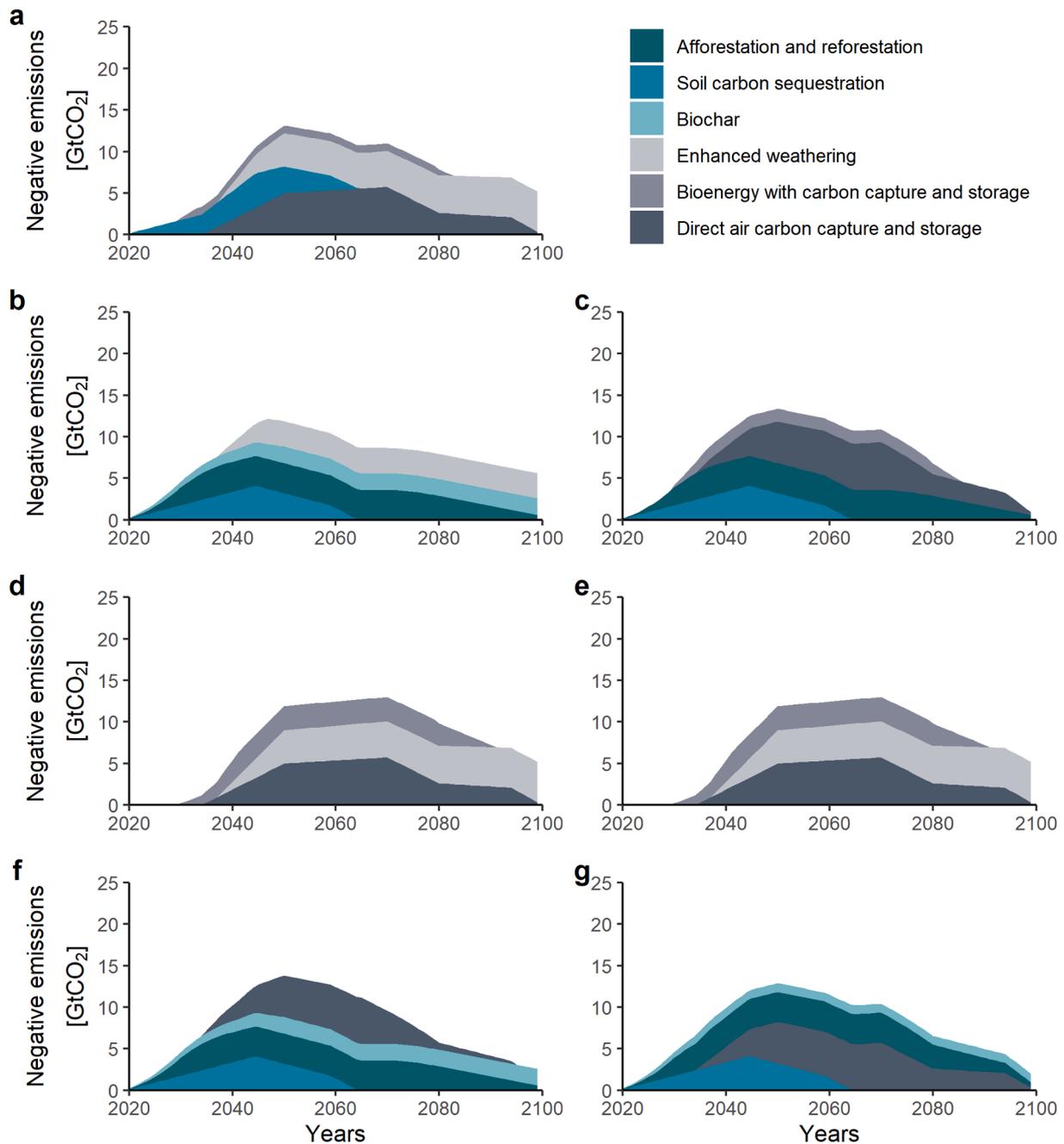
Fig. 6. NET portfolios to fulfil negative emissions need of 620 GtCO$_2$ (SSP2). Portfolio preferences include a) equal weights, b) economy, c) economy with low risk, d) climate change effectiveness, e) climate change effectiveness with low risk, f) sustainability, and g) sustainability with low risk. For SSP1 and SSP5, see Figs. S6 and S7. Green shades represent natural solutions; grey shades, engineered solutions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2100, but it is challenging because of governance barriers due to the large number of actors involved (Minx et al., 2018). Altogether, the EQ portfolio offers the most promising mix of NETs. It prioritizes DACCS, the top performing NET overall, and SCS, a no-regret solution, given its high positive side impacts and possible net negative cost opportunities. Under EQ, both DACCS and SCS would need to be fully deployed even for the optimistic scenario SSP1. For a higher demand of negative emissions, e.g., in SSP2, EW and BECCS deployment would complement the mix. Such high share of engineered solutions (DACCS, EW, and BECCS) seems reasonable, considering their superior effectiveness. Indeed, because of EQ's large share of effective NETs, its mix resembles CC and CC_lr portfolios, both prioritizing all engineered options. EQ's prioritization of SCS over EW and BECCS has two benefits: it reduces

risks related to techno-economic feasibility, and avoids a larger environmental burden-shifting mainly from large-scale BECCS deployment.

3.5. Framework's usefulness and limitations

The proposed framework provides a transparent, quantitative evaluation of NETs' key attributes and the ideal technology mix under diverse plausible portfolio preferences. To make the best use of the results, we discuss here the framework's strengths, limitations, and potential improvement areas.

The framework inherits the strengths and limitations of MCDA, on which the technology evaluation and ranking are based. MCDA's systematic approach has proven increasingly valuable to tackle similar
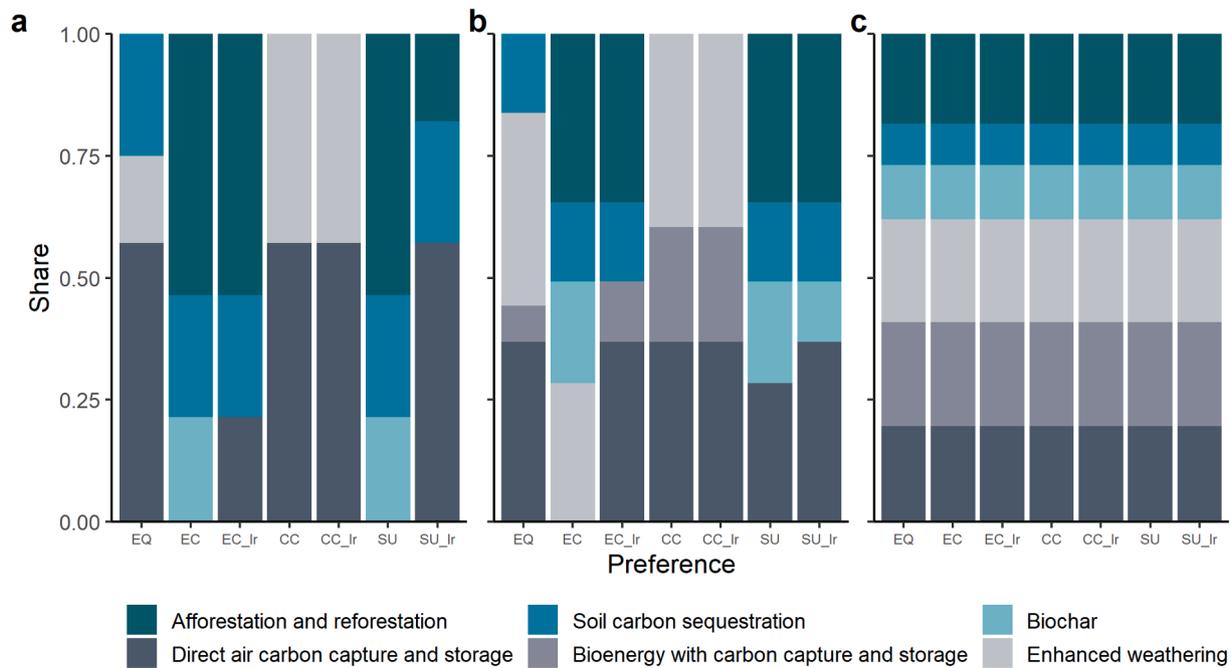
Fig. 7. Technology shares for all preference portfolios aiming to fulfil negative emissions need of a) 400 GtCO$_2$ (SSP1), b) 620 GtCO$_2$ (SSP2), and c) 1180 GtCO$_2$ (SSP5). Portfolio preferences: equal weights (EQ), economy (EC), economy with low risk (EC_lr), climate change effectiveness (CC), climate change effectiveness with low risk (CC_lr), sustainability (SU), and sustainability with low risk (SU_lr). For another deployment setting, "as soon as possible" (ASAP), see Fig. S8. Green shades represent natural solutions; grey shades, engineered solutions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
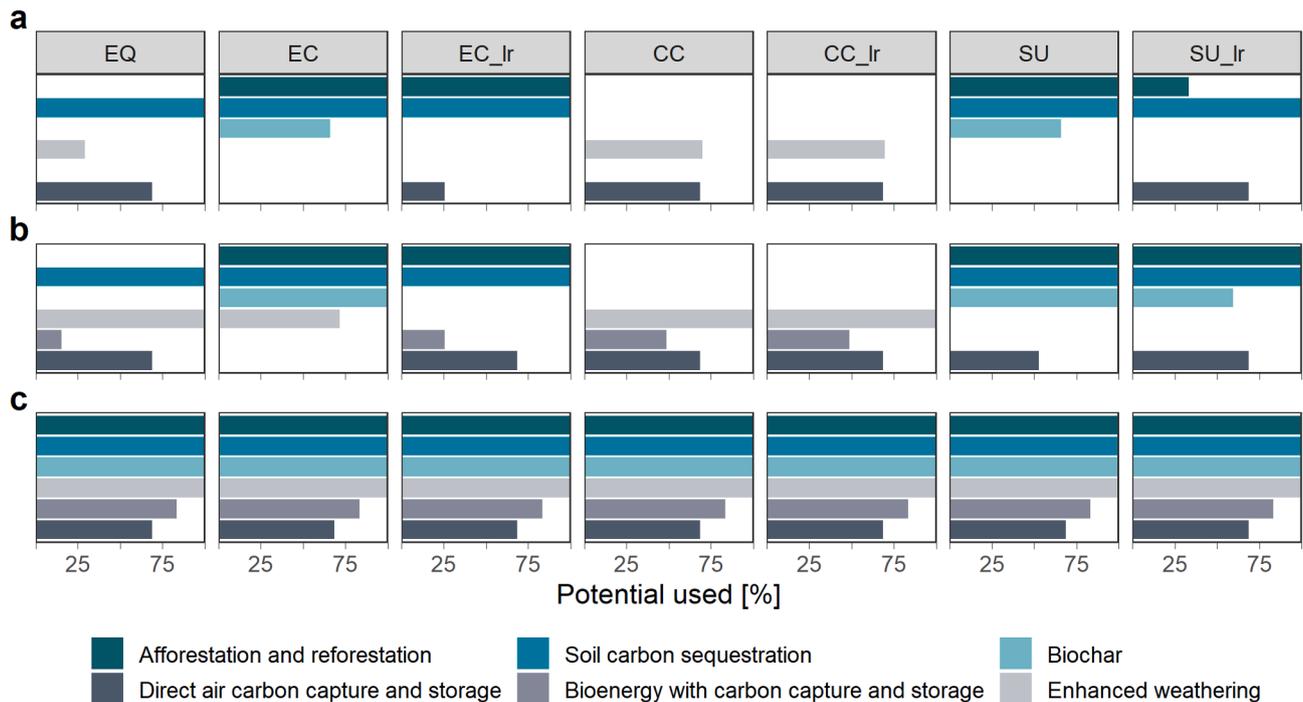
Fig. 8. Carbon dioxide removal potential used by technology and portfolio aiming to fulfil negative emissions need of a) 400 GtCO$_2$ (SSP1), b) 620 GtCO$_2$ (SSP2), and c) 1180 GtCO$_2$ (SSP5). Portfolio preferences: equal weights (EQ), economy (EC), economy with low risk (EC_lr), climate change effectiveness (CC), climate change effectiveness with low risk (CC_lr), sustainability (SU), and sustainability with low risk (SU_lr). See NET potential estimates in Fig. 4, which are based on parameters in Table 3. For another deployment setting, "as soon as possible" (ASAP), see Fig. S9. Green shades represent natural solutions; grey shades, engineered solutions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

problems (e.g., in sustainable energy systems) involving high uncertainty, different forms of data, and diverse interests and objectives. To further strengthen its usefulness in making rational decisions, diverse

styles of MCDA can be applied. The definition of criteria weights is crucial, as they directly influence the results (Wang et al., 2009). To understand the impact of criteria weights and also to represent plausible

Table 4
Portfolios' aggregated performance, considering their technology mix under SSP2 (shown in Fig. 7). Portfolio preferences: equal weights (EQ), economy (EC), economy with low risk (EC_lr), climate change effectiveness (CC), climate change effectiveness with low risk (CC_lr), sustainability (SU), and sustainability with low risk (SU_lr). For SSP1 and SSP5, see Tables S10 and S11.

	Feasibility			Climate change effectiveness			Side impacts			Average	CV
	Tech.	Econ.	Gov.	Effect	Time.	Perm.	Environ.	Econ.	Soc.		
EQ	5.6	8.7	6.4	6.9	5.7	8.5	3.6	7.1	5.6	6.5	24%
EC	6.8	9.7	4.8	4.4	2.3	3.8	6.3	6.4	5.3	5.5	38%
EC_lr	7.9	9.0	5.9	5.0	5.1	5.3	5.2	6.6	6.2	6.2	22%
CC	5.3	8.5	6.7	7.1	6.1	9.8	2.5	7.1	4.6	6.4	34%
CC_lr	5.3	8.5	6.7	7.1	6.1	9.8	2.5	7.1	4.6	6.4	34%
SU	7.6	9.3	5.4	4.4	4.1	3.8	6.3	6.4	6.3	5.9	30%
SU_lr	7.7	9.2	5.7	4.8	4.8	4.4	6.0	6.4	6.4	6.2	25%
Average	6.6	9.0	5.9	5.7	4.9	6.5	4.6	6.7	5.6		
CV	18%	5%	12%	23%	28%	43%	37%	5%	14%		

preferences of stakeholders, we defined seven different alternative weightings. The plausible preferences were defined based on the authors' judgment and also on past similar studies in sustainable energy. Moreover, we include in the Supplementary Information a sensitivity analysis to estimate the impact of plausible variations in the portfolio preferences (weightings) and the evaluations assigned (scores) on the portfolios. For a high need for NETs (SSP5), since it requires almost the full potential of all NETs, the mix in the portfolios would not change. For a low need for NETs (SSP1), only a small part of the technology mix could change; and for a medium need (SSP2), the variations in the mix become even smaller. DACCS, the most prominent option across portfolios, showed little variation in most cases. Overall, the technology mix and the contributions of each technology would largely remain unchanged. This exercise provides a useful stress test of the method. Further, alternative weightings could be defined, for instance, by incorporating input from actual stakeholders.

The selection of the criteria is also critical because it determines what to evaluate. Based on the literature review, and particularly on the comprehensive assessment of NETs by expert groups, the selected criteria are expected to represent NET's key aspects. The nine aspects selected, grouped under three categories (feasibility, climate change effectiveness, and side impacts) provide both a comprehensive and an intuitive overview of a NET's overall performance. Nonetheless, the specific evaluation of some aspects can improve with either more accurate data or alternative, more intuitive metrics. For instance, as a proxy for technical feasibility, we use the NETs' technology readiness level (TRL). A more accurate metric could be an estimate of the probability of NETs to reach maturity, e.g., by 2050, similar to the evaluation that we presented for economic feasibility. The evaluation of economic feasibility could also improve. For instance, keeping the same point of reference that we are considering (the carbon price in the future), a detailed statistical analysis for different years could more accurately quantify the likelihood of NETs' cost-effectiveness.

Beyond the strengths and limitations of the MCDA framework, we defined constraints to NET deployment, which also affect the resulting mix of technologies. The constraints represent ambitious but realistic deployment levels, based on mostly the same literature sources (as summarized in Table 3) to avoid favoring some technologies over others. The early deployment that we assume can certainly turn out overambitious; nonetheless, the opposite is also possible. DACCS adoption is particularly uncertain. On the one hand, its potential is seemingly unrestricted by obvious biophysical constraints, unlike the potential of other NETs. On the other hand, given the current early stage of this technology, it is uncertain whether DACCS can be phased in as fast as assumed. Considering the adoption of similar technologies, as explained by Realmonte et al. (2019), DACCS adoption could be quite fast (increasing up to 1.5 $GtCO_2$ per year, in line with our assumptions), and its peak potential could result much larger than our assumptions (30 $GtCO_2$ per year, instead of the 7 $GtCO_2$ per year that we assume by the end of the century). Breyer et al. (2019) explain in detail how to reach a

DAC capacity above 10 $GtCO_2$ in 2050. Assuming a similar growth rate as for solar photovoltaics, a DAC capacity of 100 $MtCO_2$ per year would need to be installed by 2030. In our case, we assume that such a capacity is only reached in 2035. Despite the late start (compared to the assumption of Breyer et al.), even a more conservative growth rate (around half the factor of solar PV) would suffice to achieve the capacity of 5 $GtCO_2$ per year in 2050 that we are considering. "An essential precondition for a continued development and cost-scaling of DAC is sustained investments into the technology, from today onwards" (Breyer et al., 2019). One of the goals of this study is precisely to help influence the development of the most promising technologies. Therefore, the assumed potential of DAC and other NETs is expected to be realistically achievable, assuming decisive technology and policy support in the coming years.

More broadly, the definition of optimal technology portfolios considers only a global perspective. A more nuanced approach would consider regional opportunities, where the evaluation of the alternatives can differ from the global assessment. Such regional perspective could prove particularly valuable to more accurately understand the performance of technologies with similar scores under particular portfolio preferences.

This study, together with past research, sheds light on critical uncertainties to evaluate NETs' overall performance. Despite the uncertainties, our evaluation of NETs delivers a valuable comparative assessment of NETs' critical aspects. We found that, generally, groups of experts agree on the relative performance of each technology. Likewise, each technology is expected to achieve the potentials presented here, if properly incentivized. Hence, policymakers and other stakeholders can use the framework and its results as a guiding tool to facilitate the objective assessment of NETs. Such a discussion is urgently needed, given NETs' already pressing implementation timeline to safely deliver their climate mitigation potential (e.g., by preventing backstop reliance late in the century).

4. Conclusions

Only an optimized portfolio, with the right technology mix timely deployed, will help harness NETs' climate risk-mitigation potential in a sustainable way. Suboptimal solutions can be infeasible, ineffective, and can even create larger problems through their collateral impacts: BECCS's massive deployment by the end of the century would be unsustainable, and AR alone cannot be considered an effective climate change mitigation solution. The rapidly dwindling carbon budget calls for urgent choices to define the right mix of carbon avoidance and removal for reaching the 1.5 °C target (van Vuuren et al., 2017). Suitable NET portfolios can effectively complement climate mitigation strategies, but their window of opportunity is quickly closing, even before the alternatives are openly discussed. For instance, low-cost measures, particularly AR, need time to overcome major governance barriers when they are already late to achieve their full carbon removal potential this

century. Conversely, effective NETs, like DACCS and EW, require decisive technology development support today to reduce emissions when estimated (Sanz-Pérez et al., 2016). Also, while the storage requirement from DACCS and BECCS seems feasible (Supplementary Information), the two NETs depend on CCS deployment, which is critically off-track (IEA, 2019). Realistic NET solutions, like the technology portfolios presented here, can provide a useful new benchmark to compare carbon avoidance measures – from lifestyle changes to technology solutions – against carbon removal measures. An optimized, timely deployed NET portfolio, largely consisting of highly effective engineered NETs (primarily DACCS) and SCS, is an overall superior alternative to the default NET portfolios considered until now. While researchers further investigate the ideal NET portfolio, policy-makers must carefully consider the costs and risks of the best current alternatives and deliberately choose the best path to solve the climate emergency.

CRediT authorship contribution statement

O. Rueda: Conceptualization, Formal analysis, Visualization, Writing - original draft. **J.M. Mogollón:** Writing - review & editing. **A. Tukker:** Writing - review & editing. **L. Scherer:** Conceptualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2021.102238.

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