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Marginal Abatement Footprint Curves for Climate Change Mitigation

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Marginal abatement cost curves are widely used as an effective means of visualizing trade-offs between emissions reduction and cost. They involve plotting multiple mitigation options on rectangular coordinates, with cumulative abatement as the horizontal axis and specific abatement cost as the vertical axis. The options are arranged in order of ascending specific cost such that, for any given marginal cost threshold, the corresponding cumulative abatement can be readily determined and easily communicated to decision-makers. This approach is very effective for decision support and can potentially be applied to constraints other than cost. In this paper, an extension of this technique is developed for decarbonization measures while considering secondary environmental footprints instead of cost. A case study on six terrestrial Negative Emissions Technologies (NETs) using global sequestration potentials is used to show how trade-offs between climate change mitigation and land or water footprints can be visualized using these Marginal Abatement Footprint (MAF) curves. The results show that targeting an annual negative emission of 8.8 Gt CO_2/y requires a MAF of at least 58 Mha/Gt CO_2 for land, and at least 1.3 × 10^{-5} Gt/Gt CO_2 for water. Based on the MAF thresholds applied in the study, water is more limiting than land.

1. Introduction

The urgency of emissions reduction measures is the key message of the third instalment of the IPCC's Sixth Assessment Report (AR6) (IPCC, 2022a). The strategies highlighted in the report include turning to renewable energy or zero to low-carbon energy sources, improving efficiency, cutting non-CO_2 emissions, accompanying fossil fuel use with carbon capture and storage (CCS), and deploying negative emissions technologies (NETs) (IPCC, 2022a). NETs that capture CO_2 from the atmosphere for storage in a different environmental reservoir have increasingly become an important addition to the portfolio of emission reduction strategies due to their ability to biophysically and economically achieve the Paris Agreement targets (Fuss et al., 2018).
Marginal Abatement Cost (MAC) curves have been used to illustrate the economics of emissions reduction measures (Nauclér and Enkvist, 2009). The concept is based on the energy conservation supply curves dating back to the 1980s (Meier et al., 1982). McKinsey & Company developed a global MAC curve for climate change mitigation, promoting the method for climate policy and decision analysis (Nauclér and Enkvist, 2009). The MAC curves involve plotting multiple mitigation options on rectangular coordinates, with cumulative abatement as the horizontal axis and specific abatement cost as the vertical axis. There are two approaches to constructing MAC curves, the traditional or expert-based and the model-based (Kesicki and Ekins, 2012). The expert-based approach utilizes the technological costs of abatement measures, derived from individual assessments (Kesicki and Ekins, 2012). On the other hand, the model-based approach derives the cost and emissions potential by running models such as energy systems models (Kesicki, 2013). For both cases, the options are arranged in order of ascending specific cost such that, for any given marginal cost threshold, the corresponding cumulative abatement can be readily determined and easily communicated to decision-makers.

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The advantages of using MAC curves include the visualization of comparable solutions within and among sectors, prioritization according to cost-effectiveness aiding policy and investment discussions, and investigation of where new technologies fit in the MAC curve (Ibrahim and Kennedy, 2016). On the other hand, the method has been criticized due to the lack of transparency in cost calculations, and limitations in handling negative costs, uncertainties, and intertemporal aspects (Kesicki and Ekins, 2012). To address the limitations of the traditional MAC, other methods of ranking abatement options have been proposed. For example, a paper proposed the Y-factor method which has the easy visualization feature of MAC but is more transparent and has a broader set of indicators (Chappin et al., 2020).

Since the popularization of MAC curves by McKinsey & Company, it has been widely used in global (Nauclér and Enkvist, 2009), regional (Khabbazan and von Hirschhausen, 2021), national (Nurfajrin and Satiyawira, 2021), and sectoral (Huang and Wu, 2021) levels in evaluating emissions reduction strategies. Although NETs have now become unavoidable to address hard-to-abate residual emissions in the energy sector (IPCC, 2022a), demonstrations of MAC curves on NETs are currently scarce. Foo (2017) developed a MAC-like approach using graphical Pinch Analysis to identify viable NETs. A paper developed a novel algebraic targeting technique in MAC curves to obtain the minimum MAC (mini-MAC) curves for CO_2 emissions reduction planning (Lameh et al., 2022). The method was then demonstrated for planning the energy mix, carbon capture utilization and storage (CCUS), and NETs (AR, BECCS, and DACCS) (Lameh et al., 2022). Another study included biomass co-firing with CCS as a means for negative emissions using an energy systems model and subsequent MAC curves (Nurfajrin and Satiyawira, 2021). These papers utilize the technological costs of NETs to build the MAC curves. Aside from technological costs, NETs also have significant environmental impacts on the land, water, and other resources that need to be considered (Smith et al., 2016). Although Mathematical Programming can be used to solve such resource constraint problems, MAC curves have an advantage in terms of easy visual communication to decision-makers with technological detail (Kesicki, 2013). Compared to another graphical approach, Pinch Analysis, MAC curves visually show the marginal cost, signifying the “willingness to pay” in decision making. So far, no studies have been found extending MAC curves to environmental footprints.

In this paper, an extension of the traditional MAC methodology is developed for decarbonization measures while considering secondary environmental footprints instead of cost in a Marginal Abatement Footprint (MAF) curve. The proposed method will benefit decision-making scenarios where specific resources such as land or water are limited. A case study on NETs is used to show how trade-offs between climate change mitigation and land or water footprints can be visualized using these MAF curves. The rest of the paper is organized as follows. Section 2 presents the problem statement. Section 3 discusses the methodology to construct the MAF curve. Section 4 illustrates the methodology in a case study on NETs. Section 5 gives the conclusion of this paper.

2. Problem Statement

The formal problem statement can be stated as follows: given a set of candidate abatement measures $(N_1, N_2, \dots N_i)$, their respective environmental footprints MF_i, and greenhouse gas (GHG) abatement potentials ΔG_i. Given a MAF threshold MF_T. A graphical method should determine the abatement measures to be chosen to meet the MAF threshold MF_T. The graphical representation should also enable the determination of the cumulative abatement potential G, which can be delivered based on the threshold, the corresponding Marginal Abatement Footprint MF at any given abatement target G_T, and the total footprint F. To address this problem, the proposed method requires two important data, the environmental footprints, and the GHG abatement potentials of the candidate abatement measures.

3. Proposed Method

This section describes the proposed graphical MAF method based on MAC curves. Here, it is assumed that the environmental footprints (MF_i), and GHG abatement potential (ΔG_i), of the candidate abatement measures N_i, are available. The steps are as follows.

(S1) Arrange the abatement measures N_i, in increasing MAF.

(S2) Prepare the MAF graph by plotting the GHG abatement potential G on the horizontal axis (in t CO_2) and the Marginal Abatement Footprint MF on the vertical axis (in unit/t CO_2).

(S3) Generate the curve so that each labelled bar depicts the results of an abatement measure N_i. The width of the bar represents the GHG abatement potential (ΔG_i) of measure N_i in t CO_2, while the height of the bar depicts the environmental footprint MF_i of abating 1 t of CO_2. The first bar is the abatement measure with the lowest environmental footprint (N_1) among the candidates and begins at the origin as shown in Figure 1a.

(S4) Plot the results for the next abatement measures. Each succeeding measure should begin immediately after the results of the preceding measure as shown in Figure 1b.

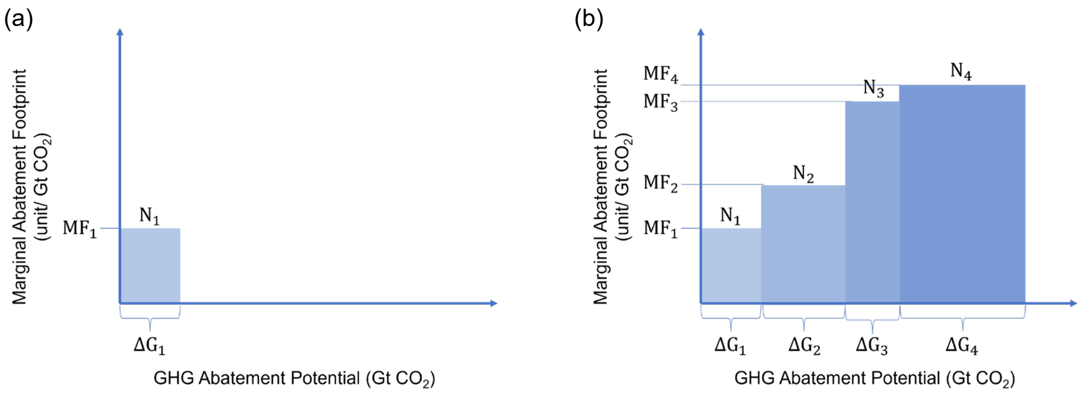

Figure 1: Procedure (a) S3 and (b) S4 in the generating the MAF curve

(S5) Further analysis can be made after plotting all the candidate abatement measures. Given a MAF threshold (MF_T), the choice of GHG abatement measures should only include the options equal or below the threshold. In the example shown in Figure 2a, the choice abatement measures are N_1, N_2 and N_3. The cumulative GHG abatement potential can be calculated from these choice abatement measures using Eq(1). In the example, the cumulative GHG abatement potential G is given by the summation of ΔG_1, ΔG_2, and ΔG_3 (Figure 2a). The total footprint (F) can then be calculated by getting the total area of the bars using Eq(2) by multiplying each bar's width by its height and getting the summation.

$$G = \sum_i \Delta G_i \,, \; MF_i \leq MF_T \quad \forall i \tag{1}$$

$$F = \sum_i MF_i \Delta G_i \,, \; MF_i \leq MF_T \quad \forall i \tag{2}$$

(S6) Inversely, an abatement target (G_T) will give the Marginal Abatement Footprint (MF) required to meet the target. Eq(3) and Eq(4) shows the general formula to calculate the total footprint (F). In the example shown in Figure 2b, the total footprint (F) includes the areas of bars N_1, N_2 and N_3, plus a partial area of the bar N_4.

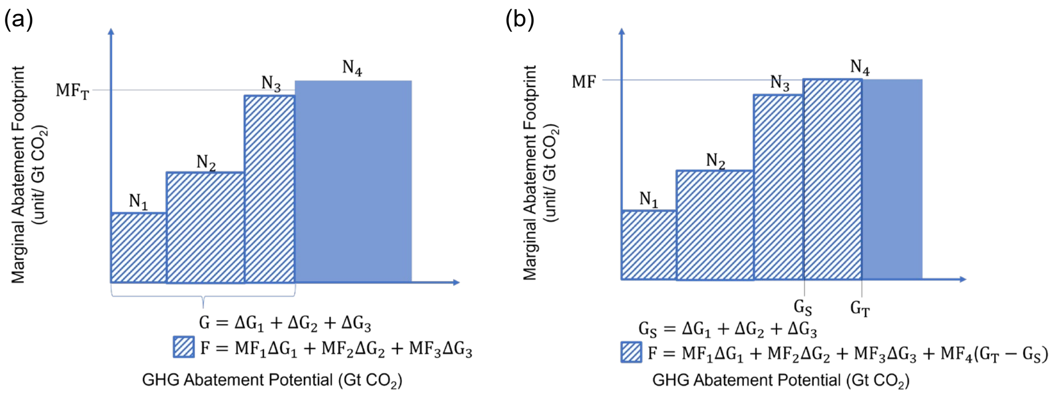

Figure 2: Procedure (a) S5 and (b) S6 in the generating the MAF curve

$$G_S = \sum_i \Delta G_i \,, \; G_S \leq G_T \quad \forall i \tag{3}$$

$$F = \sum_i MF_i \Delta G_i + MF_{i+1}(G_T - G_S) \,, \; G_S \leq G_T \quad \forall i \tag{4}$$

4. Case Study

The land and water footprints of NETs present sustainability concerns in their large-scale implementation (IPCC, 2022a). A case study demonstrating the proposed method using the land and water footprints of terrestrial NETs is illustrated. The considered NETs include afforestation/reforestation (AR), bioenergy with CO_2 capture and storage (BECCS), direct air carbon capture and storage (DACCS), soil carbon sequestration (SCS), biochar (BC), and enhanced weathering (EW). The current example makes use of global data; however, site-specific information like available technology and enabling conditions in national and regional scenarios is recommended (IPCC, 2022a). The average global annual negative emissions potentials of terrestrial NETs in 2050 (Rueda et al., 2021), as well as the average land and water footprints, were taken from published literature, given in Table 1. The data on BECCS is from a study using *Panicum virgatum* (switchgrass) and *Miscanthus* spp. biomass (Fajardy and Mac Dowell, 2017), while the data on AR are based on tropical *Eucalyptus* spp. (Smith and Torn, 2013). Soil carbon sequestration (SCS) approaches involve modifying existing practices in agroforestry, agroecology, conservation agriculture, and landscape management; it was assumed that SCS has an insignificant land impact (Brack and King, 2021). The land footprint for BC includes the land use for growing biomass (Brack and King, 2021). Compared to the other NETs, BC and SCS will have an insignificant impact on water footprint (Smith, 2016). For DACCS, renewable energy (excluding photovoltaics) and natural gas are used as energy sources; DACCS land use is very low (Fajardy and MacDowell, 2017). The EW data is based on basalt and dunite rocks applied to croplands (Strefler et al., 2018). The water requirements of DACCS and EW are based on the global scenario (Smith et al., 2016).

Two scenarios are demonstrated for each footprint. In scenario 1, the MAF threshold ($\mathrm{MF_T}$) is given, while in scenario 2, the annual negative emissions target ($\mathrm{G_T}$) is given. For illustrative purposes, it is assumed that the MAF threshold ($\mathrm{MF_T}$) for land is 10 Mha/Gt CO_2, and for water is 1.0 × 10^{-6} Gt/Gt CO_2. The annual negative emissions target $\mathrm{G_T}$ is up to 8.8 Gt CO_2/y between 2025 to 2100 to meet the 1.5 ˚C Paris Agreement target (IPCC, 2022b).

Table 1: Average negative emissions potentials, land, and water footprints of terrestrial NETs

NETs	Negative Emissions Potential in 2050 (Gt CO_2/y) (Rueda et al., 2021)	Land use/ footprint (Mha/Gt CO_2)	Water use/ footprint (Gt/Gt CO_2)	Sources
BECCS	2.75	114	800	Fajardy and MacDowell (2017)
AR	2.05	3.0	1600	Smith and Torn (2013)
SCS	3.5	0	0	Brack and King (2021)
BC	1.25	58	0	Brack and King (2021)
DACCS	2.75	0.14	1.3×10^{-5}	Fajardy and MacDowell (2017)
EW	3	85	7.25×10^{-8}	Strefler et al. (2018)

BECCS - Bioenergy with CO_2 capture and storage, AR - afforestation/reforestation, SCS - soil carbon sequestration, BC - biochar, DACCS - direct air carbon capture and storage, EW - enhanced weathering

4.1 Analysis of land footprint

The marginal abatement land use curve is generated using the potentials and land footprint data in Table 1. The resulting graph is shown in Figure 3. In the first scenario, the given MAF threshold ($\mathrm{MF_T}$) for land at 10 Mha/Gt CO_2 is used to determine the choice of NETs. Only SCS, DACCS, and AR, which are the options with minimal land requirements, are included (Figure 3). The options add up to a cumulative negative emission (G) equal to 8.3 Gt CO_2/y. By getting the sum of the areas of the selected NETs, the total footprint (F) is determined to be 6.535 Mha as shown in Figure 3. In the second scenario, a target negative emission ($\mathrm{G_T}$) of 8.8 Gt CO_2/y is given. This scenario requires additional technology, BC, and a higher Marginal Abatement Footprint (MF) of 58 Mha/Gt CO_2. The total footprint (F) for the second scenario is equal to 35.535 Mha, which is 5.4 times higher compared to scenario 1 as shown in Figure 3. The graphical method clearly shows the technical choices for scenarios where the land use is limiting. The graphical method also shows the gap between the footprint threshold and the required threshold to meet the negative emissions target, as well as the resulting footprint for each scenario.

4.2 Analysis of water footprint

The same method is applied to the water footprint. Using the potentials and water footprint data in Table 1, the graph in Figure 4 is generated. In the graph, the vertical axis is converted to a log scale to accommodate the large discrepancies between the values. Using the given MAF threshold ($\mathrm{MF_T}$) for water at 1.0 × 10^{-6} Gt/Gt CO_2

in scenario 1, the choice NETs only include SCS, BC, and EW which are the options with insignificant water footprints (Figure 4). The cumulative negative emissions (G) from these choices is equal to 7.75 Gt CO_2/y. By getting the sum of the areas of the selected NETs, the total footprint (F) is determined to be 2.18 × 10^{-7} Gt/Gt CO_2 as shown in Figure 4. For the second scenario, the target negative emissions (G_T) at 8.8 Gt CO_2/y requires additional technology, DACCS, and a higher Marginal Abatement Footprint (MF) of 1.3 × 10^{-5} Gt/Gt CO_2. The total footprint (F) of scenario 2 is equal to 1.39 × 10^{-5} Gt/Gt CO_2, which is 63.8 times higher than scenario 1. As with the previous example, the graphical method clearly shows the technical choices for scenarios where the water use is limiting and shows the gap between the footprint threshold and the required threshold to meet the negative emissions target. The MAF threshold for water resulted in a lower negative emission (G) of 7.75 Gt CO_2/y, compared to that of the land case study (8.3 Gt CO_2/y), indicating that water use is more limiting than land use. The two examples illustrate that NETs will require land and water resources to deliver a target negative emission. NETs will be needed to achieve net zero emissions but will put pressure on the resources (IPCC, 2022a). The proposed MAF method provides an approach to decision making based on the "willingness to pay" using environmental resources.

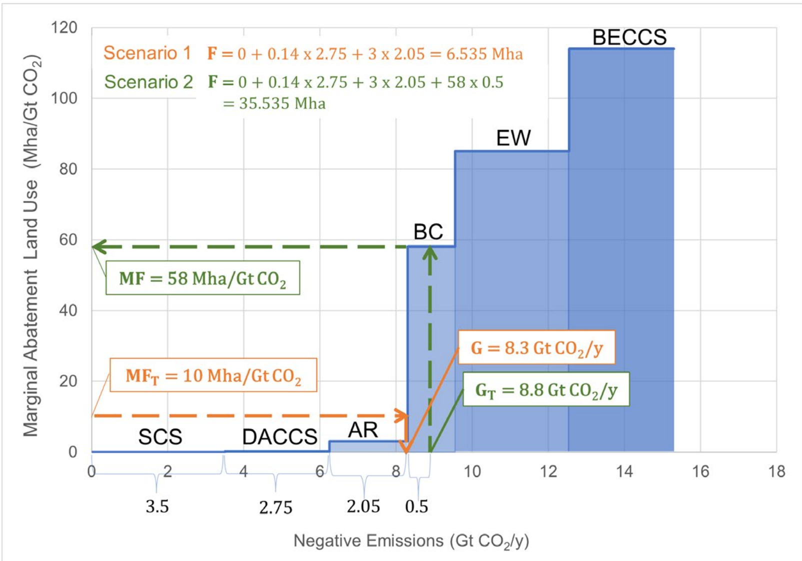

Figure 3: Analysis of the land use/footprint

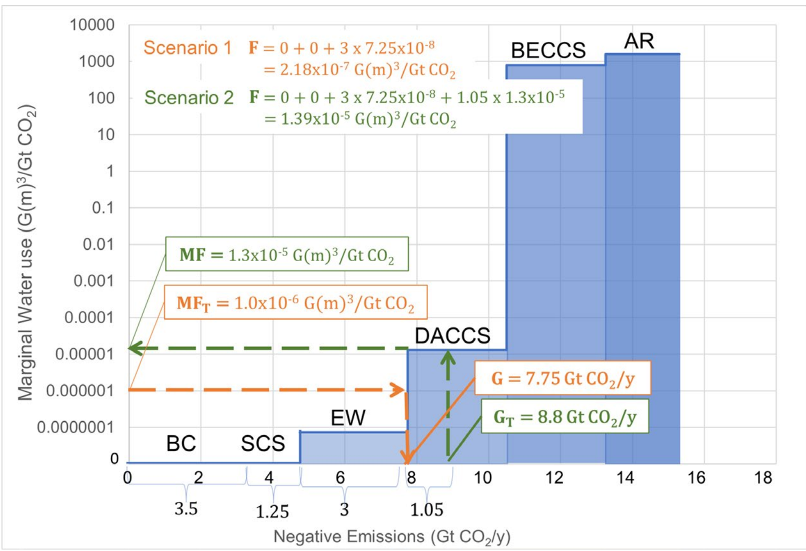

Figure 4: Analysis of the water use/footprint

5. Conclusions

A graphical method using MAF curves is proposed. The method is based on the traditional MAC methodology but replaces the cost with other environmental footprints. The GHG abatement measures are arranged in order of ascending environmental footprint such that, for any given MAF threshold, the corresponding cumulative abatement can be readily determined and easily communicated to decision-makers. Compared to Pinch Analysis, the MAC approach visually shows the marginal cost or footprint thresholds, signifying the "willingness to pay" in decision making. The method is demonstrated in a case study on NETs using land and water footprint examples. In both examples, the graphical method clearly shows the technical choices for scenarios where either land or water use is limiting. The approach also shows the gap between the footprint threshold and the required threshold to meet an abatement target. A limitation of this method is that the total environmental footprint cannot be directly obtained from the graph and must be calculated by getting the areas of the selected abatement measures. Caution must be exercised in the selection of the final technology portfolio, as it should depend on site-specific circumstances, technology availability, and enabling conditions. Future work on the method can consider multi-objective and other indicators. The relationship of this method to Pinch Analysis should also be rigorously established. Implementation of other abatement ranking methods that address the limitations of MAC such as the Y-factor, can also be explored.

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References

Brack D., King R., 2021, Managing land-based CDR: BECCS, forests and carbon sequestration, Global Policy, 12(S1), 45–56.
Chappin E.J.L., Soana M., Arensman C.E.C., Swart F., 2020, The Y factor for climate change abatement – A method to rank options beyond abatement costs, Energy Policy, 147, 111894.
Fajardy M., Mac Dowell N., 2017, Can BECCS deliver sustainable and resource efficient negative emissions? Energy and Environmental Science, 10(6), 1389–1426.
Foo D.C.Y., 2017, Extended graphical technique for the evaluation of carbon dioxide emission reduction projects, Process Integration and Optimization for Sustainability, 1(4), 269–274.
Fuss S. et al., 2018, Negative emissions - Part 2: Costs, potentials and side effects, Environmental Research Letters, 13(6), 063002.
Huang Y.H., Wu J.H., 2021, Bottom-up analysis of energy efficiency improvement and CO_2 emission reduction potentials in the cement industry for energy transition: An application of extended marginal abatement cost curves, Journal of Cleaner Production, 296, 126619.
Ibrahim N., Kennedy C., 2016, A methodology for constructing marginal abatement cost curves for climate action in cities, Energies, 9(4), 227.
IPCC, 2022, Summary for policymakers. In: Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge, UK and New York, NY, USA.
Kesicki F., 2013, Marginal abatement cost curves: combining energy system modelling and decomposition analysis, Environmental Modeling and Assessment, 18(1), 27–37.
Kesicki F., Ekins P., 2012, Marginal abatement cost curves: A call for caution, Climate Policy, 12(2), 219–236.
Khabbazan M.M., von Hirschhausen C., 2021, The implication of the Paris targets for the Middle East through different cooperation options, Energy Economics, 104, 105629.
Lameh M., Al-Mohannadi D.M., Linke P., 2022, Minimum marginal abatement cost curves (Mini-MAC) for CO_2 emissions reduction planning, Clean Technologies and Environmental Policy, 24, 143–159.
Meier A., Rosenfeld A.H., Wright J., 1982, Supply curves of conserved energy for California's residential sector, Energy, 7(4), 347–358.
Nauclér T., Enkvist P., 2009, Pathways to a low-carbon economy: Version 2 of the global greenhouse gas abatement cost curve, McKinsey & Company <www.mckinsey.com/business-functions/sustainability/our-insights/pathways-to-a-low-carbon-economy> accessed 21.05.2022.
Nurfajrin Z.D., Satiyawira B., 2021, Abatement cost for selectivity negative emissions technology in power plant Indonesia with aim/end-use model, IOP Conference Series: Earth and Environmental Science, 894(1), 012011.
Rueda O., Mogollón J.M., Tukker A., Scherer L., 2021, Negative-emissions technology portfolios to meet the 1.5 °C target, Global Environmental Change, 67, 102238.