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ORIGINAL ARTICLE

Inter-sectoral prioritization of climate technologies: insights from a Technology Needs Assessment for mitigation in Brazil

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Abstract
Technological development is key for national strategies to cope with the Paris Agreement's goals. Technology Needs Assessments (TNAs) aim to identify, prioritize, and diffuse climate change mitigation and/or adaptation technologies in developing countries. Their methodology includes a multi-criteria decision analysis (MCDA) framework but, although many countries already conducted a TNA, literature lacks discussions on country-specific processes for a TNA, as it usually follows a one-size-fits-all approach. This paper provides empirical evidence on the importance of country-driven processes that help shaping international programmes into country-specific needs and capabilities. It presents lessons learned from a tailored process for identification, prioritization, and selection of mitigation technologies in the scope of a TNA project for Brazil, an exceptional case of a developing country with strong capacity in integrated assessment modelling (IAM) scenarios for guiding its climate strategies. A previous IAM scenario result allowed pre-selecting technologies in six key economic sectors, while other TNAs prioritized no more than three. This allowed the elaboration of an overall ranking from the MCDA, in contrast to sectoral rankings that are mostly employed in other countries' TNAs. The overall ranking serves not only as a basis for the selection of priority technologies but also provides information on the integrated innovations framework for climate technologies in the country. Further specific findings of the tailored Brazilian TNA approach are discussed in the paper in order to call for the importance that a technology transfer project should not only be country-driven but also conducted through a country-specific process.

Keywords Brazil · Technology Needs Assessment · Mitigation · Multi-criteria analysis · Analytic hierarchy process

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1 Introduction

Ninety-five percent of the 147 non-Annex I parties that presented intended Nationally Determined Contributions mentioned the term "technology" in their voluntary goals (UNFCCC 2016). Therefore, to effectively achieve the global goals accorded in the Paris Agreement, technology innovation in developed as well as in developing countries is an enabling condition (de Coninck et al. 2018). Innovation can be understood as a novel application of an idea in practice (Fagerberg 2006). Some of them are categorized as radical innovations (Byrne et al. 2012), which are those directly related to an invention — the first occurrence of an idea (Fagerberg 2006). Yet, much technology innovation also comes from processes of incremental improvements or adaptations of an application to a different context, such as a new country or firm (Ockwell and Byrne 2016). Particularly in the case of developing countries, adaptative innovation is of central importance (Byrne et al. 2012; Ockwell and Byrne 2016).

This calls for the importance of national systems of innovation (NSI) (Byrne et al. 2012). The NSI concept acknowledges that both radical and incremental innovation occur in a network of multiple actors (e.g. research institutes/universities, companies/entrepreneurs, government, financial sector, users/consumers), their interlinkages and the institutional framework within which they operate (Sagar 2009; Byrne et al. 2012; de Coninck and Puig 2015; Ockwell and Byrne 2016). In fact, NSI in many developing countries is weak or highly fragmented, which hinders their innovation capabilities (de Coninck and Puig 2015; de Coninck and Sagar 2015b; Ockwell and Byrne 2016).

In that regard, international technology transfer mechanisms are useful for fostering climate technology innovation in developing countries (Sagar 2009; de Coninck and Puig 2015). Yet, the success of such cooperation mechanisms requires a tailored process which considers the specificities of the technology as well as the national circumstances (Sagar 2009; Pandey et al. 2022). Hence, many authors argue for the need for bottom-up country-driven approaches in climate technology cooperation processes, led by the demands of the recipient country (Liu and Liang 2011; Boldt et al. 2012; Boyd 2012; de Coninck and Puig 2015; Ockwell and Byrne 2016; Puig et al. 2018; Prasad and Sud 2021).

Technology Needs Assessments (TNAs) can be defined as a group of country-driven activities which aims to the identification, prioritization, and diffusion of environmentally sound technologies in terms of climate change mitigation and/or adaptation (de Coninck and Puig 2015; UNEP DTU 2020). It is a long-standing multilateral effort aimed at promoting technology transfer: since 2001, more than 80 countries published their reports in the official TNA database, and there are some 60 that specifically address the identification and prioritization of climate change mitigation technologies (Puig et al. 2018; Hofman and van der Gaast 2019; UNEP DTU 2020).

There are three activities in a TNA project, namely (i) identification and prioritization of sectors and technologies, (ii) barrier analysis and enabling framework identification, and (iii) technology action plan (TAP) (Haselip et al. 2019). The first step results in the so-called TNA reports. It contains significant information on the country's climate and development priorities, which is obtained from the inputs of the engagement of relevant local stakeholders (de Coninck and Puig 2015; Puig et al. 2018; Hofman and van der Gaast 2019). Hofman and van der Gaast (2019) argue that a country can use the results from a TNA project on its national climate strategy, in particular its Nationally Determined Contribution (NDC). The authors claim that the degree to which the TNA results could contribute to the country's NDC is essentially related to its climate NSI strength: for least developed countries and small island developing states, the TNA is helpful for capacity building, strategy development, and the preparation of projects for investment with international support; for emerging markets and newly-industrialized countries, the TNA can serve as a participatory approach for climate strategy development; for developed countries, the whole TNA process is unnecessary since they generally rely on strong databases and modelling capacities, but the participatory approaches and multi-criteria decision analysis (MCDA) can be used to fine-tune modelled strategies. Such fine-tuning comes in the aid of overcoming the limitations of a purely cost-based strategy that usually results from these robust models. In that regard, Grubb et al. (2021) argue that omitting important benefits of a low carbon transition, such as the creation and development of new markets and jobs, the impacts on air quality and energy prices and the climate risks, creates a bias towards inaction.

In this sense, the case of Brazil presents interesting characteristics for study: despite being a developing country, which makes it eligible for a TNA project, Brazil offers a strong capability in terms of integrated assessment modelling to support its climate strategy. The first Brazilian NDC was also supported by an early version of the BLUES (Brazilian Land Use and Energy Systems) integrated assessment model (IAM) (Rathmann 2017; Rochedo et al. 2018). Moreover, a scenario ran with the global IAM COFFEE (COmputable Framework For Energy and the Environment model), developed in Brazil, was used as one of the five Illustrative Mitigation Pathways (IMP-Neg) in the Six Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2022). Thus, lessons learned from a TNA report for Brazil can provide valuable insights not only for the elaboration of TNAs in other developing countries but also for complementing results from IAM scenarios for developed countries with a participatory MCDA which considers other aspects than greenhouse gas (GHG) reduction potentials and costs. Yet, a critical discussion on the methodology of identification and prioritization of climate technologies applied to a TNA case study does not exist in the current literature, despite the alleged potential contributions of this process in terms of structuring national climate strategies (Hofman and van der Gaast 2019) and strengthening NSI through the engagement of relevant stakeholders (de Coninck and Sagar 2015b). Furthermore, while there is agreement on the need for a country-driven approach for TNAs (Boldt et al. 2012; Ockwell and Byrne 2016; Puig et al. 2018; Hofman and van der Gaast 2019), the literature lacks discussions on country-specificity to the TNA process.

Hence, this study reviews the processes and results from the first phase of a TNA project for mitigation technologies in Brazil. The purpose is to bring the main lessons learned from the application of a participatory MCDA methodology for identifying, prioritizing, and selecting climate technologies in the country guided by some key questions: How climate technologies were pre-selected for the MCDA?; Which MCDA tool was employed in the analysis?; How were the criteria chosen and how good are they for an MCDA?; How were the priority sectors and technologies determined from the MCDA results? For that, Sect. 2 presents general information on the TNA process and a brief review of a sample of previous TNA country reports for mitigation technologies. In Sect. 3, the methodological procedure adopted in the Brazilian TNA for the selection of priority technologies is thoroughly presented, from the pre-selection of technologies to the MCDA steps and the selection of technologies from the ranking. In Sects. 4 and 5, results are presented and discussed, respectively. This includes analyses of the criteria weighting process, the technologies' performance in the selected criteria, and the overall ranking obtained from the MCDA. Also, the consistency of the MCDA tool is tested, and a statistical analysis is proposed for assessing the quality of the criteria set selected for the MCDA. Finally, Sect. 6 summarizes the final considerations of this paper, its limitations, and proposes topics for future studies.

2 Technology Needs Assessments

2.1 TNA's institutional set-up

Technology Needs Assessments are designed to support developing countries in meeting their goals of mitigation and/or adaptation to climate change through technological development. The general structure of a TNA project at a national level involves the figure of a National Project Coordinator (NPC), a team of National Consultants (NCT), and Sectoral Working Groups, in addition to a National Steering Committee (NSC). The NPC is the focal point of the UNFCCC in the country and is responsible for leading the overall project efforts, facilitating communication between components, forming networks, acquiring information, and coordinating and communicating products. The NCT has the role of conducting the analytical part of the TNA's work, which includes the proposition and application of the method of identification and prioritization of technologies. This must have the input of stakeholders, who actively work on the project, organized in Sectoral Working Groups according to their respective expertise. Finally, the NSC is the instance of the project's high-level guidance, which should ensure political acceptance and dissemination of the TNA products and results, respectively. The NSC meets only a few times during the execution of the project, first when the project's team is established and then again at the conclusion phase of the TAP (Haselip et al. 2019). Figure 1 outlines the overall structure of a TNA project.

There are three activities in a TNA project, namely (i) identification and prioritization of sectors and technologies, (ii) barrier analysis and enabling framework identification, and (iii) technology action plan. In general, the outcome of the first step is referred to as a "TNA report", while the others are referred to as "Barrier Analysis and Enabling Framework" and "TAP report", respectively. Thus, this article uses these nomenclatures to name each step. "TNA Project" is used for reference to the full scope of the project.

In the TNA Brazil project, the NCT is composed of academic experts in climate technology analysis from two Brazilian universities, the Federal University of Rio de Janeiro (UFRJ) and the Federal University of Minas Gerais (UFMG). The NPC of the project is a member of the Ministry of Science, Technology, and Innovations of Brazil and the NSC is composed of the General Climate Coordination of the Ministry of Science, Technologies, and Innovations, the Brazilian Cooperation Agency of the Ministry of External Relations, and the United Nations Environment Programme. Additionally, a Technical Advisory Committee (TAC) was instituted by a Ministerial Ordinance in order to: (i) monitor and support the execution of the TNA Brazil project's work plan; (ii) appoint groups of key actors to compose the sectoral working groups; (iii) contribute with technical guidance in all stages of the project execution; (iv) review, in its area of expertise, products prepared by the NCT; and (v) promote broad participation of key actors in the project execution process (BRASIL 2019a). The TAC's composition was also instituted by a Ministerial Ordinance (BRASIL 2019b) with members legally appointed by the ministers of state of Mines and Energy; Environment; Economy;

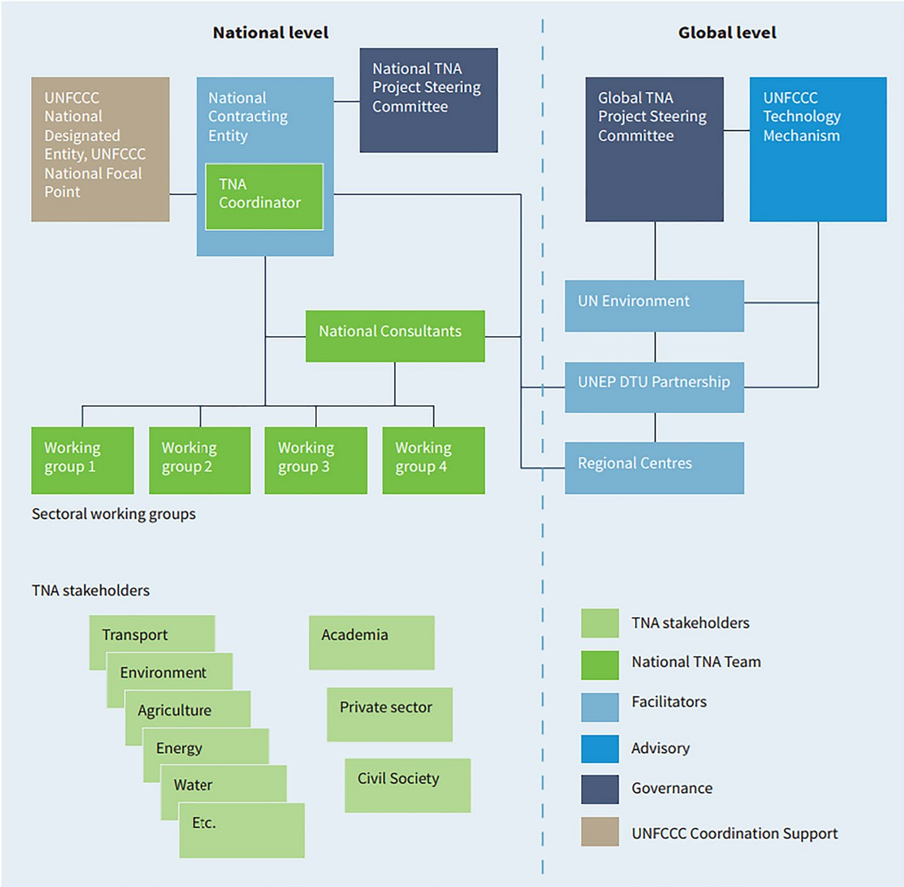

Fig. 1 TNA institutional set-up. Source: (Haselip et al. 2015)

Agriculture, Livestock, and Supply; Regional Development; Infrastructure; and Science, Technologies, and Innovations, as well as members of the Energy Research Company, the National Petroleum, Natural Gas, and Biofuels Agency, the National Confederation of Industry, the Financier of Studies and Projects, and a designated national authority of the Green Climate Fund. The institution of the TAC with such composition members followed the recommendations proposed by Hofman and van der Gaast (2019), who argue that an interministerial committee "creates active ownership of the process across the government and across sectors". Moreover, involving high-level policymakers enhances the likelihood that there will be political backing for the results of the TNA and financial experts should be involved throughout the whole process for reality checks on the feasibility of identified technologies and proposed projects (Hofman and van der Gaast 2019).

Three Working Groups of stakeholders were formed, with the themes of (i) agriculture, forestry, and other land uses (Afolu), (ii) industry and energy, and (iii) transport, waste, and buildings. The stakeholders invited by the NPC are associated members of the Brazilian Research Network on Global Climate Change (Rede CLIMA) and other experts appointed by the TAC from the public and private sectors and civil society with notable knowledge about these sectors.

2.2 TNA reports on mitigation in other countries: criteria choice, weighting methodology, and prioritized sectors

As of June 2021, more than 80 countries had already made their TNA reports available in the official TNA project database, of which 63 refer to mitigation technology options (UNEP DTU 2020). Of these, the 48 available in English, Spanish, or Portuguese were sampled for a review[1] on their choice of criteria, the applied methodology for weighting the criteria, and the sectors selected for prioritization.

The general methodology for ranking mitigation technology options is an MCDA, as recommended in the TNA step-by-step guide (Haselip et al. 2015). In this type of analysis, each technology is evaluated by experts on a set of criteria, which are defined and weighted by consensus among stakeholders, national consultants, and the NPC.

Regarding the choice of criteria, 87.5% of TNA reports assessed use a two-level approach to criteria, where the first level represents a more general theme (such as “environmental”) and the second includes specific points related to the previous level (such as “air quality”). The most selected first-level criteria are “social”, “economic”, “environment”, and “cost”, which are present respectively in 77%, 75%, 73%, and 60% of the sample. Only 31% of the TNAs in the sample selected a first-level “institutional” or “political” criterion.

Fifty-four percent of the TNA reports analysed used budget allocation for weighting the criteria, in which stakeholders are asked to distribute a predefined number of points (usually 100) among criteria, according to their perceived importance of each criterion. In another 13%, the methodology is similar, except that the stakeholders do not distribute points but rate the criteria in a defined range (generally 1 to 10) and the total scores are then normalized. Another 13% use a swing weights approach, in which the weights of each criterion are extracted from the deviation found in the scores that are assigned to the technologies. The greater the deviation verified in the performance of a criterion among the set of technologies, the greater the weight attributed to the criterion. Ten percent of TNAs choose to simply assign equal weights to all criteria and the rest use other methods, such as Colombia’s TNA report, which adopts the analytical hierarchy process (AHP) methodology (Colombia 2013).

Regarding sectors, energy is prioritized in 77% of the TNA reports, followed by transport (52%) and waste (35%). The number of shortlisted technologies for scoring ranges from 7 to 57, with a median value of 18. In 58% of the TNAs, the technologies of all sectors are assessed by the same set of criteria, while the others use specific criteria for each sector. In the sample of TNA reports assessed, only the TNA report from Costa Rica presents an overall ranking for the technologies of all sectors. All the others present a single ranking for each sector.

[1] The TNA reports reviewed are from Afghanistan, Argentina, Azerbaijan, Bangladesh, Belize, Bhutan, Cambodia, Colombia, Cook Islands, Costa Rica, Cuba, Dominican Republic, Ecuador, Eswatini, Fiji, Gambia, Georgia, Grenada, Guyana, Honduras, Indonesia, Jordan, Kazakhstan, Kenya, Laos, Lebanon, Liberia, Malawi, Mauritius, Moldova, Mongolia, Mozambique, Myanmar, Pakistan, Panama, Peru, Philippines, Rwanda, Seychelles, Sri Lanka, Sudan, Tanzania, Thailand, Uganda, Uruguay, Vanuatu, Vietnam, and Zambia.

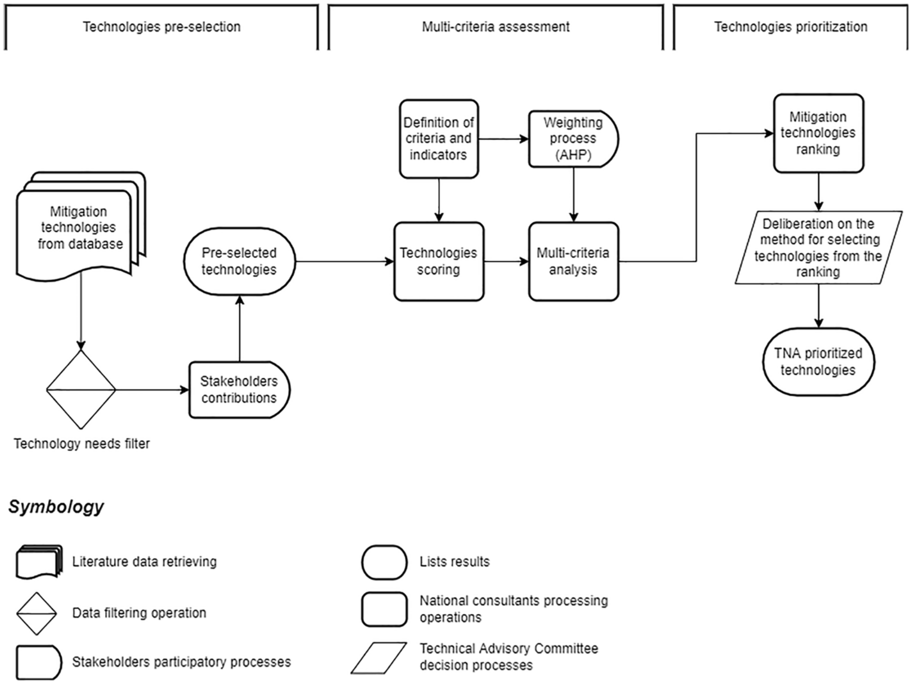

Fig. 2 TNA Brazil methodological procedure flowchart

3 The TNA Brazil's MCDA method

The multi-criteria procedure adopted in the Brazilian TNA Report (Rathmann et al. 2017) follows the basic steps provided in the TNA project's step-by-step guidelines (Haselip et al. 2019). Yet, given some specificities of the Brazilian context, it presents some differences from what has been reviewed in the previous TNA reports (Sect. 2.2). First, the technologies are pre-selected from a database built as a result of a previous study for Brazil, which applied integrated assessment models (IAMs) to select the least-cost, optimal groups of technologies across the economic sectors in different long-term future scenarios (Rathmann 2017). Also, the assignment of weights to the criteria is based on a participatory MCDA-AHP method, instead of the commonly preferred budget allocation method. Moreover, instead of pre-selecting sectors/sub-sectors and promoting different analyses for each, this study uses the same set of criteria for comparing the technologies of all sectors and generates a unique ranking for all options. This provides an integrated overview of the mitigation options framework, which is further discussed in the following sections. A broad view of the methodological procedure is depicted in Fig. 2.

3.1 Pre-selection of technologies

The meaning of "technology" may vary according to the perspective of different actors (Boldt et al. 2012; de Coninck and Sagar 2015a; Haselip et al. 2019), while Nygaard and

Hansen (2015) call for the importance of defining a clear technology concept for the success of a TNA. Definitions vary from a strictly technical standpoint — engineering and machines — to a broader idea, including behavioural and organizational elements (Geels 2002, 2014; Olsen and Engen 2007). Nygaard and Hansen (2015) provide three dimensions of technology, namely hardware, which expresses the tangible aspects, such as products and equipment; software, which comprises the knowledge associated with the production and use of the hardware; and orgware, which accounts for the institutional framework involved in the adoption and diffusion of a novel technology. This study adopts a definition based on the TNA guidebook (Haselip et al. 2019), in which technology is "a piece of equipment, technique, practical knowledge or skills for performing a particular activity". This definition is associated with the TNA's objective of providing a broad set of information to develop a TAP addressing the barriers associated with the technologies valleys of death[2] (Jenkins and Mansur 2011; Haselip et al. 2015; Rissman et al. 2020).

The selection of technologies assessed in the TNA Brazil came from the database built in a previous optimization analysis, from which a longlist of 450 promising technologies for carbon mitigation in Brazil is extracted. This analysis refers to a project entitled "Mitigation Options of Greenhouse Gas (GHG) Emissions in Key Sectors in Brazil"[3] (Rathmann 2017), which applied an early version of the BLUES model and the OTIMIZAGRO[4] model, an IAM, and a spatially explicit land use simulation model, respectively, to evaluate least-cost solutions in mitigation scenarios for Brazil. From this database, a shortlist of 80 mitigation technology options with technology needs is drafted, which is presented to stakeholders for their feedback and contribution. Finally, the list of pre-selected technologies is presented to the TAC for its validation.

Other TNA reports have only considered mitigation options for previously prioritized sectors or sub-sectors, usually no more than two or three, as the effort for identifying technologies for all key sectors could not be manageable for a 2-year project (Hofman and van der Gaast 2019). However, the availability of a previous database of mitigation options for Brazil allowed for the inclusion of technologies for all of the country's key economic sectors, as defined by Rathmann et al. (2017): (i) industry, (ii) energy, (iii) transportation, (iv) residues, (v) buildings, and (vi) Afolu. Furthermore, the industrial sector is further divided into three subsectors that represent the major sources of process emissions in the Brazilian

[2] The so-called valleys of death comprise a common set of market barriers that are endemic to most technology innovations. They relate to the unavailability of private finance in two transitory stages of the technology development: early, from the laboratory to the proof-of-concept, referred to as the "Technological Valley of Death"; and later, from demonstration to commercial scale, referred as the "Commercialization Valley of Death" (Jenkins and Mansur, 2011).

[3] The webpage of the project containing all the documents (in Portuguese) can be accessed in the following link: <https://antigo.mctic.gov.br/mctic/opencms/ciencia/SEPED/clima/opcoes_mitigacao/Opcoes_de_Mitigacao_de_Emissoes_de_Gases_de_Efeito_Estufa_GEE_em_SetoresChave_do_Brasil.html>

[4] The BLUES model is a perfect-foresight, least-cost optimization model for Brazil, which was built on the MESSAGE (Model for Energy Supply Strategy Alternatives and Their General Environmental Impacts) platform. The model is designed to simulate the competition between technologies and energy sources to meet the demand for food and energy services (exogenous to the model, including lighting, heating/cooling requirements, mechanical energy, and mobility, among others), with the objective of minimizing the total cost of the system. OTIMIZAGRO is a nationwide, spatially explicit model that simulates land use, land use change, forestry, deforestation, and regrowth under various scenarios of agricultural land demand and deforestation policies for Brazil with a 25 ha (500 × 500 m) resolution. The model allocates land uses and calculates GHG emissions/removals based on crop aptitude and profitability calculated by using regional selling prices, production and transportation costs (Rochedo et al. 2018).

industry (cement, chemicals, and iron and steel) and an additional aggregate subsector that contains cross-cutting measures.[5] The energy sector is split into four categories: oil and gas exploration and production (E&P), oil refining, power generation, and biofuels. The measures for Afolu are represented in two categories, namely agriculture (including livestock) and other land uses. For the other key sectors, no subdivisions are adopted.

3.2 Multi-criteria decision analysis

From the list of 80 pre-selected technology options, the TAC and the NPC determined the selection of 12 for the elaboration of a TAP, based on the Brazilian TNA project's budget, team and time constraints. Therefore, the pre-selected technologies were compared and ranked in order to identify the most suitable ones for the main goal, based on a set of defined criteria.

A multi-criteria decision analysis (MCDA) is conducted for prioritizing the technologies, as suggested in the TNA guidebook (Haselip et al. 2019). The MCDA is a methodological approach that enables the decision-maker to compare and rank alternatives based on a set of diverse, non-related criteria. In other words, it enables one to identify an optimal solution, given a specific final objective, by reaching a compromise between criteria. These criteria can be quantitative or qualitative, and from different natures, what makes the decision a non-trivial problem.

Thus, to perform the MCDA, the following steps are taken: (i) defining the relevant criteria; (ii) weighting the selected criteria; (iii) giving scores to each alternative regarding its performance in each criterion; (iv) ranking the alternatives based on its score in each criterion and the relative weight of the respective criterion.

3.2.1 Definition of criteria

The broad purpose of this step in the TNA project is to identify the most promising technology options from key economic sectors in Brazil in terms of their potential to generate climate and non-climate benefits to the country. The MCDA criteria must be aligned to this objective and therefore reflect the adequacy of a technology within the Brazilian context. In general, similarly to what De Luca (2014) states, the criteria should be represented by typical targets that a technology option should guarantee, in the context of the established main goal. It is also important to ensure that the criteria are as independent of each other as possible. Strong correlations should be avoided so that there are no multiple counts of a single aspect, which could distort the MCDA result (Haselip et al. 2015).

Hence, the strategy to choose the decision criteria for this study takes into consideration the three dimensions of technology (Nygaard and Hansen 2015) and is based on four pillars: assess the technical aspects inherent to a technology (hardware dimension); assess the national context in terms of knowledge capacity for absorbing the technology (software dimension); assess how the technology fits within climate, science and technology policies, and the sectorial framework contexts in the country (orgware dimension); and assess the

[5] Cross-cutting measures are not focused on a specific industrial segment, rather can be adopted in more than one subsector. For example, a pipeline network infrastructure can transport CO_2 from and to different industrial sources, coupling the biofuels, industrial process emissions, electricity generation, and oil and gas E&P segments (da Silva et al. 2018; Tagomori et al. 2018).

co-benefits that the deployment of the technology could bring to the country, in environmental, social, and economic terms, linking those criteria to one or more of the United Nations Sustainable Development Goals (SDGs) (UN 2020), whenever pertinent. Co-benefits are important elements to be considered in MCDAs for prioritizing climate technologies, particularly when they are used to refine the results from IAMs (Ürge-Vorsatz et al. 2014). Such co-benefits follow the definition of Deng et al. (2017), which includes the intended and unintended (or ancillary) positive and adverse effects of a climate mitigation action.

Therefore, a set of 15 sub-criteria is defined by the NCT and divided into four criteria groups: (i) technological, (ii) physical, (iii) socio-economic, and (iv) institutional. The technological criteria relate to aspects that are inherent to the technology and fundamentally related to the scope of the analysis, namely its mitigation potential, mitigation costs, and level of technological development and vulnerability. The physical and socioeconomic criteria are more context-sensitive and reflect the on-climate benefits that the deployment of a technology can bring he Brazilian society. These are deeply related to nationally achieving SDGs. Lastly, the institutional criteria aim at assessing a technology in terms of the main Brazilian climate policies, sectoral strategies, and existing regulatory frameworks. Table 1 contains the description of the selected criteria. Section 3.2.3.1 describes a method employed in this study to assess the quality of the selected criteria by the level of correlation between them, obtained from the technologies scoring.

3.2.2 Weighting of criteria

In the UNEP DTU Partnership framework (Trærup and Bakkegaard 2015; UNEP DTU 2021), some methods are presented to assign weights to criteria: equal weights, statistical methods, and participatory methods. However, it is desirable that a collaborative process is adopted, with the involvement of relevant stakeholders from different sectors (Rogat 2015; Hofman and van der Gaast 2019). Hence, a participatory method able to reflect the views and priorities of stakeholders is desirable. Among the participatory methods, two are highlighted by UNEP DTU (2021): budget allocation and the analytical hierarchy process (AHP).

In the budget allocation participatory method, each stakeholder is given a budget of 100 units to distribute among criteria. This method is advised to be used in TNA studies due to its simplicity. It can be seen that it is the most employed method across the other countries' reviewed TNA studies (refer to Sect. 2.2). However, this method is better suited for analyses with few criteria, as the cognitive effort for distributing points for a large number of criteria may be too high (Doyle et al. 1997; van Til et al. 2014).

The other participatory method mentioned by the framework is the AHP (UNEP DTU 2021). Instead of comparing all criteria simultaneously, such as in the budget allocation method, in the AHP, respondents are asked to compare criteria in pairs. Due to that, in comparison to other methods, the AHP requires smaller cognitive efforts (De Luca 2014) and allows the improvement of the accuracy of judgments (Şahin 2021). Thus, it is suited for analyses comprising larger sets of criteria. Nonetheless, if a problem has too many alternatives, it leads to a combinatorial explosion in the number of pairwise comparisons. In this case, the AHP is employed solely for assigning weights to criteria and not for assessing the alternatives (Şahin 2021).

Moreover, the AHP enables the assessment of quantitative and qualitative indicators based on expert and/or stakeholder judgments. Hence, it makes it possible to incorporate,

Table 1 Description of the selected criteria and sub-criteria

Criteria	Description	Sub-criteria	Description
Technological (TEC)	Contains indicators with a technical perspective, assessing engineering-level features of the technology	Technology readiness (TR)	Represents the maturity status of the technologies globally, i.e. whether its applications are still on lab-scale (low) or are already commercial (high)
		Mitigation potential (MP)	Technology's GHG emission reduction potential related to the current practices [A]
		Mitigation cost (MC)	Cost of the technology per unit of CO_2 mitigated (US$/$tco_2$)[A]
		Vulnerability to climate change (VC)	Reflects how the technology is exposed to the expected effects of climate change (e.g. mean temperature increase, sea level rise, variability of renewable resources and increased risk of extreme climate events) compared to the current practices
Physical (PHY)	Consists of indicators that reflect the impacts of the technology on the physical environment, based on selected UN's SDGs	Health and pollution reduction (SDG3) (HP)	Impacts of the technology regarding pollutants generation throughout the production chain
		Impact on water availability (SDG 6) (WR)	Impacts of the technology on the availability of water resources for society[B]
		Impact on food production (SDG 2) (FP)	Impacts of the technology on agriculture, land use and food security[C]
		Impact on biodiversity (SDG 15) (BD)	Effects of the technology on biodiversity
Socio-economic (SOE)	Incorporates indicators that address the effects of the technology adoption on social and economic conditions	Impact on energy availability (SDG 7) (EN)	Impact of the technology on the amount of energy available to society, energy resources use efficiency, renewable energy promotion, energy access and energy infrastructure modernization
		Jobs and income generation (SDG 10 and SDG 8) (JI)	Potential impacts of the technology on social inequalities reduction in Brazil, focusing on jobs creation and income generation[D]
		Competitive advantages of the country (SDG 9) (CA)	Assessment of how the technology can be benefited from being adopted in the studied country, given advantages of production factors in the country (capital, labour, and natural resources) and the national competence (scientific and technological centres, experience and ongoing research and development)

Table 1 (continued)

Criteria	Description	Sub-criteria	Description
Institutional (INT)	Incorporates indicators for the degree of compatibility of the technologies to relevant institutional features	Synergy with the country's National Strategy for ST&I (ST)	Technology's fitting within the scope of the Brazilian National Strategy for Science, Technology and Innovation (2016–2022)
		Synergy with National Climate Policies (CP)	Technology's position within the scope of the Brazilian climate policies framework[E]
		Synergy with the Country Program for the GCF (GF)	Technology's position within the scope of the "Country Program for the Green Climate Fund (GCF)"
		Institutional framework (IF)	Feasibility of the technology implementation beneath the current institutional framework, considering the existence of legal instruments, taxes incidence, barriers (economic, market, institutional, cultural), and market and government failures in the studied country

[A]In this study, the GHG emission reduction potentials and the mitigation costs are based on Rathmann et al. (2017), and the corresponding BLUES model results. [B]The BLUES model includes water requirements and water systems balances related to the mitigation options. [C]The BLUES model includes land use competition related to the mitigation options. [D]Effects on the whole value chain are considered, such as presented in PMR (2018). [E]Including the Brazilian NDC (Nationally Determined Contribution) (BRASIL 2015), RenovaBio (the Brazilian strategy for the contribution of diverse biofuels to the national energy matrix and GHG emissions mitigation plans) (BRASIL 2019c), the Low-Carbon Agriculture Plan – ABC Plan (the Brazilian mitigation and adaptation plan regarding the agriculture and farming sectors) (BRASIL 2012), and the National Climate Change Program (BRASIL 2008) account, and quantify the participants' preferences, taking into consideration tangible and intangible aspects (De Luca 2014; Le Pira et al. 2015; Estévez et al. 2021; Şahin 2021). When establishing weights, it allows measuring the trade-offs between attributes (De Luca 2014; Estévez et al. 2021). Finally, through its results, which are based on pairwise comparisons, it is possible to identify preference relationships, i.e. to determine the strength of preference for one criterion or alternative over another (Acosta and Corral 2017; Estévez et al. 2021).

AHP is one of the most extensively employed MCDA methods (Marttunen et al. 2017; Estévez et al. 2021; Şahin 2021), in part because of its simplicity. When conducting participatory processes, the AHP method is especially useful because the pairwise comparison procedure is perceived as straightforward and easily accepted by stakeholders. Moreover, it uses an additive preference function, simplifying the understanding and interpretation of results for decision-makers (De Luca 2014; Estévez et al. 2021). The AHP method is widely used in different areas of knowledge and sectors, as in the power sector (Höfer et al. 2016; Estévez et al. 2021; Şahin 2021; Vinhoza and Schaeffer 2021), forest management (Acosta and Corral 2017), and transportation (De Luca 2014; Le Pira et al. 2015). As an example, Estévez et al. (2021) reviewed 184 articles to assess how social criteria and participation mechanisms have been incorporated into decision-making processes for renewable energy technologies. Most of them (48,6%) employed AHP as the MCDA method.

However, because human judgments are inherently inconsistent and especially when dealing with complex problems with several attributes, there is the possibility of inconsistency in the pairwise comparison matrix (Höfer et al. 2016; Şahin 2021). In this context, inconsistency means that individual judgments can be affected by a lack of rationality during the analysis. The comparison matrix must also obey a transitivity condition, meaning that if alternative/criterion A is preferred to B and B to C, then A is preferred to C (Le Pira et al. 2015). The accuracy of the AHP results depends mainly on the consistency of the pairwise comparison evaluations (Şahin 2021). Due to that, the consistency of judgments must be checked in the AHP through the consistency index, which is explained in the following section.

The AHP methodological framework is thoroughly described in the Supplementary Material and its application for weighting the criteria in the Brazilian TNA report is described in the following section.

Application of the AHP method in TNA Brazil The first step of the AHP method is the proposal of a final objective, which is used as the foundation of a hierarchical structure of criteria (Saaty 1987). In this study, the final objective is to select technologies for mitigating GHG emissions while maximizing co-benefits, in agreement with the aims of the TNA_BRAZIL project. For this analysis, the AHP method is structured based on two levels of criteria to reach the final objective, containing the 4 criteria and the 15 sub-criteria (refer to Table 1). The AHP structure for this study is depicted in Fig. 3. One of the main challenges in defining the AHP structure was to identify criteria that would be relevant to all sectors, and as such, could be the basis of an inter-sectorial technology priority ranking.

The following step is the survey. This procedure aims at collecting the stakeholders' answers through the pairwise comparison of criteria (and sub-criteria). In this study, the stakeholder's inputs for the weighting process were collected from June to August 2019 in three workshops, which admitted present and remote contributions of invited stakeholders. The first workshop involved a technical team of the Brazilian Ministry of Science, Technology, and Innovations (MCTI). The second workshop involved stakeholders considered relevant for the key sectors, divided into three sectoral chambers: (i) Afolu; (ii) transport, residues, and buildings; and (iii) energy and industry. The third workshop gathered responses from the members of the TAC. Table 2 presents the institutions of the selected key sector stakeholders and the number of contributions from each entity in all three workshops.

All participants were invited to register their contributions in an electronic form, prepared in the Google Forms platform. To avoid bias throughout the process, the answers were kept in secrecy from other participants, and the stakeholders did not know what technologies have been pre-selected to be further analysed in the MCDA.

Questions were asked in 5 rounds: 4 rounds for comparing, in pairs, the sub-criteria with respect to their respective criteria group and 1 round for comparing the criteria concerning the final objective (refer to Fig. 3). The form followed the basic structure for questions: “In your opinion, for the goal of reducing GHG emissions while maximizing co-benefits, when comparing the criterion/sub-criterion X to the criterion/sub-criterion Y, X is:”, and the alternatives for answering were:

(1) Much less important
(2) Less important
(3) Equally important
(4) More important
(5) Much more important

In the present study, an adapted scale is employed in this interviewing phase, ranging from 1 (much less important) to 5 (much more important), as detailed above. This adaptation was adopted to simplify the evaluation from stakeholders since there were already several questions to be answered. Moreover, the understanding of the questions itself can be jeopardized when the decision-maker is being interviewed and not fully integrated into the MCDA process from the beginning. After the interviewing process, the 1-to-5 scale of the answers was transformed to the Saaty (1987) fundamental 1/9-to-9 scale to complete the matrices for conducting the AHP method. The equivalence procedure is described in the Supplementary Material.

To aggregate answers from multiple respondents, two aggregation methods are available: the aggregation of individual judgments (AIJ), in which the answers from multiple individuals are aggregated, forming a new individual judgement and only one priority vector is calculated for the group; and the aggregation of individual priorities (AIP) method, in which a priority vector is calculated for each individual response and then the individual priorities are aggregated in one final priority vector (De Luca 2014; Le Pira et al. 2015; Höfer et al. 2016).

In this study, the purpose of the participatory process for criteria weighting was to aggregate the opinions of several stakeholders from different sectors to reach one common viewpoint. It is worth mentioning that, given the context of the TNA process, all stakeholders are assumed to have the same weight in the final decision, regardless of their sector, type of organization, the event in which they took part, and the form of participation (remote or not) (Rogat 2015; Haselip et al. 2019). Hence, to aggregate the responses from the 47 interviewed stakeholders, the AIJ method was chosen, and the arithmetic mean of the responses was calculated, forming a new matrix for each of the 5 rounds (1 for criteria and 4 for sub-criteria).

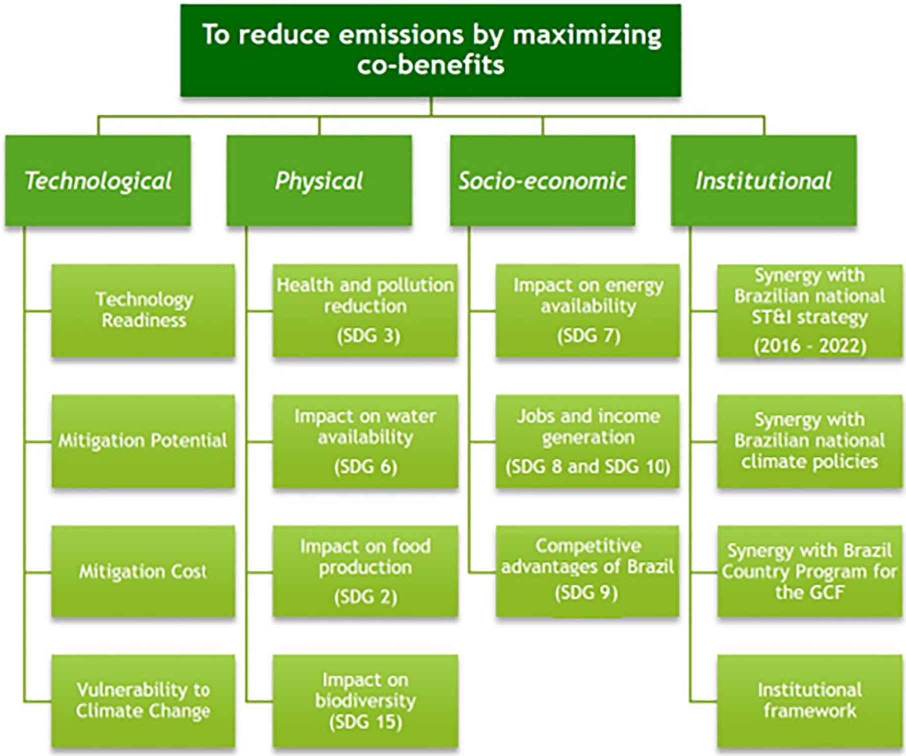

Fig. 3 AHP hierarchy, containing the final objective and the levels of criteria and sub-criteria

Finally, the priority vector was calculated for each of the 5 matrices, revealing the established weights for each criterion and sub-criterion. In addition, the consistency ratios (CRs) for all 5 matrices were also calculated. These are shown in the "Results" section (please refer to Table 4). All the calculations were performed using Microsoft Excel spreadsheets.

3.2.3 Technologies scoring

In parallel to the weighting of criteria, the pre-selected technologies are assessed according to their performance in each sub-criterion. This is done by the technology analysts of the NCT. Literature review and, when possible, quantitative assessments are used as a tool for conceiving scores, from 1 to 5. As shown in Table 3, score 1 denotes a very poor performance of the technology in the sub-criterion, while score 5 represents a very good performance. Score 3 means either an average performance or that the technology is considered neutral, i.e. does not impact the sub-criterion, depending on the context. In the case of no evident relationship between a technology and a criterion, the technology was assumed neutral and received a score of 3.

For the technology readiness, the mitigation potential, and the mitigation costs, a quantitative-based approach is used. Hence, the values for these indicators had to be normalized to fit the scores scale from 1 to 5. The remaining indicators follow a qualitative approach

Table 2 Institutions that contributed to the weighting process

Institution	Acronym	Stakeholders' perspective	Contributions
Ministry of Science, Technology, and Innovations	MCTI	Public sector	11
Ministry of Economy	ME		2
Ministry of Agriculture, Livestock, and Supply	MA		1
Ministry of Regional Development	MDR		1
Ministry of Infrastructure	Minfra		1
Ministry of Environment	MMA		1
Ministry of Mines and Energy	MME		1
Sao Paulo's State Government	SP		1
National Agency of Petroleum, Natural Gas, and Biofuels	ANP		1
Energy Research Company	EPE		1
National Institute of Technology	INT		1
Brazilian Agricultural Research Corporation	EMBRAPA		1
Centre for Strategic Studies and Management	CGEE		1
Brazil's National Institute for Space Research	INPE		1
Petrobras	Petrobras		1
CAIXA	Caixa		1
National Bank for Economic and Social Development	BNDES		1
Brazilian Innovation Agency	FINEP		1
Federal University of Rio de Janeiro	UFRJ	Academia	2
University of São Paulo	USP		2
University of Brasilia	UnB		1

Table 2 (continued)

Institution	Acronym	Stakeholders' perspective	Contributions
Brazilian Mineral Coal Association	ABCM	Private sector	1
Brazilian Association of Photovoltaic Solar Energy	ABSOLAR		1
Instituto Aço Brasil	Aço Brasil		1
Agroicone	Agroicone		1
Brazilian Biofuels Producers Association	APROBIO		1
National Confederation of Industry	CNI		1
National Confederation of Transport	CNT		1
Industry Federation of the State of Rio de Janeiro	FIRJAN		1
Light	Light		1
Charitable Association of the Santa Catarina Carboniferous Industry	SATC		1
Amazon Environmental Research Institute	IPAM	Civil society	1
World Resources Institute	WRI		1

Table 3 Technologies scoring definitions and an example for the sub-criterion "Impact on water availability"

Scoring	Definition	Example: impact on water availability (WR)
1	Very poor performance	Technology strongly reduces water availability
2	Poor performance	Technology reduces water availability
3	Average or neutral performance	Technology does not affect water availability
4	Good performance	Technology enhances water availability
5	Very good performance	Technology strongly enhances water availability

and are assessed based on relative performances. A thorough explanation of the scoring procedure for the quantitative indicators is presented in the Supplementary Material, together with a full list of the justification for each score in each technology option.

It is noteworthy that the decision to delegate technology scoring to the NCT was made to avoid possible conflicts of interest for stakeholders to determine scores for technologies they wish to promote or discourage. Such a concern for curtailing this sort of bias is also highlighted in Gambia's TNA report (Njie 2017). This comes from the assumption that stakeholders are more prone to lobby for technologies in which they have an interest, which might lead them to artificially overestimate technologies' performance on the proposed criteria. On the other hand, the academic experts in the NCT working in consensus would have no particular interest in promoting any technology and would base their scores purely on available evidence.

Quality assessment of the criteria choice A statistical analysis of the scores is performed to identify whether there are strong correlations between the criteria. This procedure aims to check the quality of the criteria set selected for the MCDA since strong correlations are undesired (Haselip et al. 2015). Given the qualitative scale adopted for the criteria scoring, a Spearman's rank correlation coefficient (SRCC) analysis is performed. This method is used to examine the relationship between two qualitative variables by comparing a set of ranks of each.

The coefficient values range from − 1 to + 1, where the positive values mean a similar trend for the scoring rankings of two criteria, while the negative values mean that the two criteria scoring rankings show an opposite trend (Zavadskas and Vilutiene 2006; Kou et al. 2012; Şahin 2021). Correlations are considered strong for absolute values of SRRC over 0.6 (Zavadskas and Vilutiene 2006). The coefficient (r_s) is calculated by Eq. 1, where "d_i" is the difference between the ranks of two criteria of a technology and "n" is the number of technologies assessed.

$$r_s = 1 - 6\frac{\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)} \quad (1)$$

3.3 Ranking of technologies and selection of priorities

After the weighting of criteria and the technology scoring process, the final valuation for each technological option can be calculated by Eq. 2, where "FV_t" is the final value of the technology "t", "$SC_{t,i}$" is the performance score of the technology "t" in the sub-criterion "i" (attributed by the technical analysts), "W_i" is the weight of the sub-criterion "i", and "W_c" is the weight of the criterion "c" related to the sub-criterion "i".

$$FV_t = \sum_{i=1}^{15} (SC_{t,i} * W_i * W_c) \quad (2)$$

After the calculation of the FV for each technology, a ranking of technologies is set. This ranking should reflect how the technologies on the list contribute to the final objective of the MCDA. A discussion is then conducted with the TAC for the selection of which technologies should be prioritized based on the results of the multi-criteria analysis and the technologies ranking. The idea is to reach a consensus on a method to select technologies from the ranking by guaranteeing that the final objective is reached with an adequate degree of fairness in the distribution of the measures for the key sectors. Four methods are proposed to select the priority technologies from the ranking that would ensure an adequate sectoral balance of the options:

(i) Ordinal selection (ORS): a selection based simply on the technology position on the ranking, regardless of the sector;
(ii) Sectoral equity selection (SES): an equal number of the best-ranked technologies for each sector is selected;
(iii) Sectoral emissions representativity selection (SER): the number of best technologies chosen for each sector is proportional to its share of the country's emissions[6];
(iv) Sub-sectoral emissions representativeness selection (SSE): the number of technologies selected per sector is similar to (iii), but they are equally distributed between the subsectors, when plausible, following the order of merit established by the ranking.

4 Results of the MCDA for TNA Brazil

Figure 4 shows the weights of the criteria and sub-criteria obtained from the AHP. Figure 5 shows the final weight of each sub-criterion, obtained by multiplying the weights of the sub-criteria by their related criterion. The SOE criterion reached the highest weight, followed by the TEC, INT, and PHY criteria. As for the sub-criteria, JI received the highest weight among the socio-economic sub-criteria. Therefore, it is the most relevant sub-criterion for the composition of the technologies' final value. WR was also considered quite more important than the other sub-criteria of its group. However, due to the low weight of the PHY criterion, its final weight was among the lowest ones in the analysis. In addition to JI, the other criteria with relatively high final weights are IF, MP, and EN. All their weights are higher than 6.6%, which would be the final weight of each sub-criterion if an equal weights approach was adopted.

The consistency ratios (CRs) for the AHP matrixes used for computing the weights for the criteria and sub-criteria are presented in Table 4. Since the CR for all matrices is less than 0.1, the comparisons for all criteria and sub-criteria are considered to be consistent.

[6] Based on the Fourth Edition of the Annual Estimates of Greenhouse Gas Emissions in Brazil (BRASIL 2017).

Fig. 4 Weights of the criteria and sub-criteria obtained from the AHP analysis

From the consulted literature and the contribution of the sectoral stakeholders, 80 technologies from all the sectors were pre-selected to be analysed. As an example of the technologies scoring process, results for nine technologies from the power sector (Table 5) are shown in Table 6 for all sub-criteria. A full list of the technologies considered in this work with a further description of them and the performance scores for each indicator is presented in the Supplementary Material.

The SRRCs, employed for identifying correlations in the scores based on the assessment of the 80 mitigation technologies, are shown in Table 7. As mentioned before, correlations are considered strong for absolute values of SRRC over 0.6 (Zavadskas and Vilutiene 2006). It can be noted that "FP" (impact on food production) presented strong correlations with "WR" (impact on water availability) and "BD" (impact on biodiversity), two of the other "Physical" sub-criteria, and also with the "Technological" sub-criterion "VC" (vulnerability to climate change). Additionally, almost all the "Institutional" sub-criteria show strong correlations with each other.

Finally, the technologies ranking is presented in Table 8. The seven best-ranked technologies overcome the score of 4.0, and most of these technologies are related to

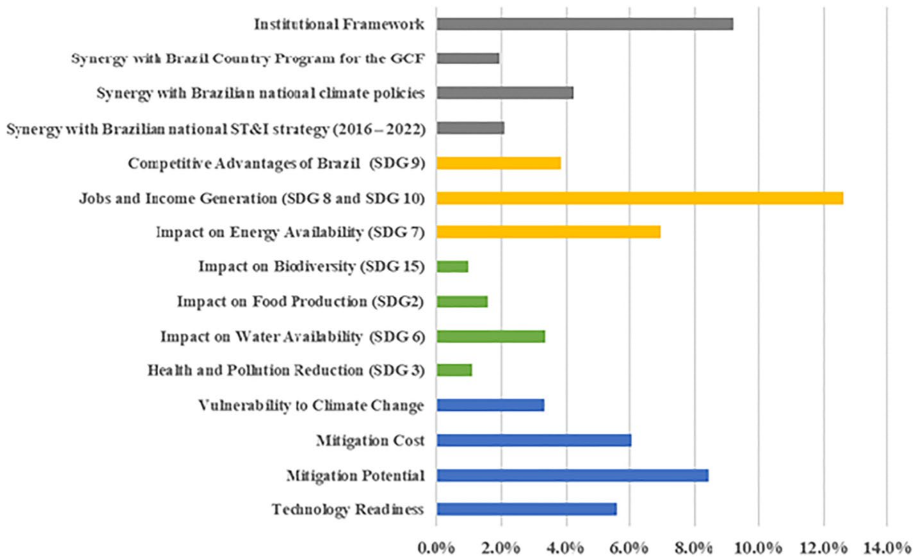

Fig. 5 Share of each score in the composition of the technology final value

Table 4 Consistency ratio (CR) for criteria and sub-criteria comparison matrices

Comparison matrices		CR
Criteria		0.03
Sub-criteria	TEC	0.08
	PHY	0.07
	SOE	0.01
	INT	0.02

Table 5 Codes for nine technologies from the power sector

Technologies	Code
Hydrokinetic turbines	E7
Pumped-storage hydropower plants	E8
Repowering hydropower plants	E9
Offshore wind energy	E10
Integrated combined cycle with biomass gasification in thermoelectric plants	E11
Concentrated solar power (CSP)	E12
Floating solar power plants	E13
CO_2 capture in natural gas-fired thermoelectric plants	E14
CO_2 capture in coal-fired thermoelectric plants	E15

Afolu value chains. In fact, the Afolu sector technologies are overall well ranked. On the other hand, technologies of the industrial sector appear most in the last positions of the ranking.

Table 6 Scores for a sample of nine 9 technologies from the power sub-sector: dark red = 1; light red = 2; yellow = 3; light green = 4; dark green = 5. (Please refer to Table 5 for the codification)

Code	TR	MP	MC	VC	HP	WR	FP	BD	EN	JI	CA	ST	CP	GF	IF
E7	3	1	4	2	4	3	3	3	5	4	5	3	4	3	3
E8	5	1	4	2	4	3	3	3	5	3	5	3	4	4	2
E9	5	1	4	3	3	3	3	3	4	3	5	3	4	3	2
E10	1	1	1	2	4	3	3	2	5	4	5	4	4	5	3
E11	3	1	2	2	4	1	1	1	4	4	5	4	4	4	3
E12	4	2	1	2	4	1	1	1	4	4	5	4	4	5	3
E13	5	1	2	2	4	4	3	2	5	4	5	5	5	5	5
E14	4	1	2	3	3	1	3	3	1	4	4	3	3	2	1
E15	4	1	2	3	3	1	3	3	1	4	3	4	3	2	1

As previously mentioned, a set of 12 priority technologies was considered by the Brazilian government and the project's team as feasible for the development of the TAP. Hence, the final step consists of arriving at a consensus regarding a method to select the priority technologies from the ranking that would ensure an adequate sectoral balance of the options. Table 9 presents the technologies with the respective sector and subsector selected for the four proposed methods.

All methods privilege the Afolu sector, which gets half of the technologies in the ORS, SER, and SSE methods and four out of the 12 places in the SES method. Most of the Afolu prioritized technologies are from the other land uses sub-sector. The transport sector also guarantees a good presence in the list of technologies for TAP, with three options for the ORS method and two for the others. The industrial sector appears without technologies contemplated for the ORS method and with two technologies for the other methods. In turn, the energy sector appears with one technology in all methods except SES, in which it reaches two. The waste sector reaches one technology in all methods and the buildings sector is contemplated with one technology by the ORS, SES, and SSE methods and none in the SER.

Finally, the overall ranking together with the results of each selection method is presented to the TAC. The Committee deliberates on which approach presents the results that are more aligned to its expectations, considering their political feasibility. In this case, the TAC decided to select the priority technologies according to the SSE method.

5 Discussion

5.1 Insights on the technology pre-selection

As mentioned in the "Introduction", Brazil is a developing country with considerable capability in terms of modelling scenarios for supporting its climate strategy, especially due to its efforts to develop its own IAMs (Rathmann 2017; Rochedo et al. 2018). A scenario round from an early version of the BLUES model was used as an important input to the Brazilian TNA by indicating a longlist of mitigation technologies for all key sectors of the country (Rathmann 2017). Yet, these previous results selected technologies based only on

Table 7 Spearman's rank correlation coefficient for the technologies' scores in each sub-criterion (SC). Strong correlations are shown in bold

SC	TR	MP	MC	VC	HP	WR	FP	BD	EN	JI	CA	ST	CP	GF	IF
TR	**1.000**	−0.147	0.139	0.025	0.042	0.113	0.107	0.103	0.251	0.240	0.015	−0.064	0.080	0.032	0.155
MP	−0.147	**1.000**	0.161	0.363	0.292	0.302	0.389	0.226	−0.083	0.153	0.172	0.324	0.221	0.193	0.103
MC	0.139	0.161	**1.000**	0.262	0.061	0.386	0.378	0.290	0.106	−0.053	0.272	0.282	0.172	0.069	0.212
VC	0.025	0.363	0.262	**1.000**	0.121	0.565	**0.693**	0.598	0.099	0.086	−0.004	0.229	0.049	0.062	0.118
HP	0.042	0.292	0.061	0.121	**1.000**	0.359	0.298	0.291	0.401	0.252	0.139	0.229	0.391	0.544	0.295
WR	0.113	0.302	0.386	0.565	0.359	**1.000**	**0.718**	0.546	0.422	−0.026	0.196	0.416	0.345	0.401	0.440
FP	0.107	0.389	0.378	**0.693**	0.298	**0.718**	**1.000**	**0.731**	0.199	0.091	0.281	0.427	0.317	0.303	0.387
BD	0.103	0.226	0.290	0.598	0.291	0.546	**0.731**	**1.000**	0.171	0.183	−0.046	0.165	0.137	0.211	0.087
EN	0.251	−0.083	0.106	0.099	0.401	0.422	0.199	0.171	**1.000**	0.130	0.195	0.311	0.396	0.430	0.382
JI	0.240	0.153	−0.053	0.086	0.252	−0.026	0.091	0.183	0.130	**1.000**	0.140	0.231	0.321	0.337	0.151
CA	0.015	0.172	0.272	−0.004	0.139	0.196	0.281	−0.046	0.195	0.140	**1.000**	0.552	0.577	0.383	0.490
ST	−0.064	0.324	0.282	0.229	0.229	0.416	0.427	0.165	0.311	0.231	0.552	**1.000**	**0.609**	0.526	**0.662**
CP	0.080	0.221	0.172	0.049	0.391	0.345	0.317	0.137	0.396	0.321	0.577	**0.609**	**1.000**	**0.801**	**0.714**
GF	0.032	0.193	0.069	0.062	0.544	0.401	0.303	0.211	0.430	0.337	0.383	0.526	**0.801**	**1.000**	0.563
IF	0.155	0.103	0.212	0.118	0.295	0.440	0.387	0.087	0.382	0.151	0.490	**0.662**	**0.714**	0.563	**1.000**

Table 8 Technologies ranking

Position	Technology	Final value	Position	Technology	Final value
1	Silviculture with native species for restoration	4.39	41	Partial or total electrification of vessels using renewable energy	3.30
2	Flex hybrid vehicles	4.18	42	Offshore wind energy	3.29
3	Use of agricultural and agro-industrial waste	4.12	43	Installation of steam recovery units in storage tanks	3.25
4	Plug-in hybrid electric vehicles	4.09	44	Implementation of flare pilots	3.22
5	Satellite monitoring	4.04	45	Repowering hydropower plants	3.22
6	Mixed planting silviculture with exotic and native species	4.03	46	Use of biomass for olefin production	3.21
7	Ethanol fuel cell electric vehicles	4.00	47	Electric turbo-compound engines	3.20
8	Precision forestry and silviculture	3.92	48	Concentrated solar power (CSP)	3.16
9	Floating solar power plants	3.90	49	Natural gas for cabotage shipping	3.16
10	Forestry genetic engineering	3.79	50	Catalytic cracking of naphtha	3.15
11	Photovoltaic solar induction stoves	3.79	51	Use of new. lighter materials in vehicles	3.15
12	Precision agriculture	3.75	52	Innovative materials for cement	3.13
13	Certification systems for chains that are deforestation-free	3.71	53	Advanced fluidized bed combustion	3.12
14	Agricultural genetic improvement with robotic phenotyping	3.71	54	Application of the HIsarna process for fusion reduction	3.12
15	Validation systems for the Rural Environmental Registry	3.71	55	Autonomous vehicles sharing	3.11
16	Light-duty battery electric vehicles	3.67	56	Gas-to-liquids (GTL)	3.11
17	Conservation and genetic improvement of native species	3.65	57	Hydrogen fuel cell electric vehicles	3.09
18	Industry 4.0	3.64	58	Integrated combined cycle with biomass gasification in thermoelectric plants	3.07
19	Alternative materials for cement	3.63	59	Transport of CO_2	3.05
20	Smart grids	3.63	60	Biobunker fuel for shipping	3.04
21	New materials for Zero Energy Buildings (ZEB)	3.62	61	Magnetic levitation (MagLev) systems for trains	3.00
22	Application of Drying, Pyrolysis and Cooling (DPC) technology in charcoal production	3.61	62	Membrane separation	2.99
23	Green diesel	3.60	63	CO_2 capture in ammonia production	2.96
24	Biodigestion of MSW for generating electricity and biomethane	3.56	64	Smart convoy systems	2.89

Table 8 (continued)

Position	Technology	Final value	Position	Technology	Final value
25	Hydrokinetic turbines	3.55	65	Electrification of aircraft using renewable energy	2.87
26	Use of renewable energy in industrial processes	3.55	66	Hybrid solar plants	2.78
27	Battery electric buses	3.54	67	Application of SIDERWIN process	2.72
28	Application of Ondatec technology in charcoal production	3.54	68	Recovery of residual heat from electric arc furnaces using the Organic Rankine Cycle	2.72
29	Renewable microgeneration plants: wind microturbines, OPV and thin film cells	3.54	69	Steam reforming of coke oven gas	2.71
30	Generation of electricity from biogas with microturbines	3.50	70	Improvement of aircraft aerodynamics	2.64
31	Waste Incineration	3.50	71	Oxygen enrichment systems	2.61
32	Partial or total electrification of trains	3.49	72	CO_2 capture with amines	2.58
33	Storage of CO_2Storage of CO_2	3.45	73	Chemical looping	2.57
34	Nutritional supplementation	3.45	74	CO_2 capture in hydrogen generation units	2.57
35	Low-carbon alternatives to Nitrogen, Phosphorus and Potassium (NPK)	3.45	75	CO_2 capture in oil and gas production	2.57
36	Second generation ethanol	3.43	76	Use of H2 obtained from renewable sources for the production of ammonia and methanol	2.54
37	Genetic improvement in beef cattle	3.43	77	CO_2 capture in natural gas-fired thermoelectric plants	2.51
38	Pumped-storage hydropower plants	3.36	78	Blast furnace gas collection and reforming using the IGAR process	2.51
39	Biojet (aviation biofuel)	3.35	79	CO_2 capture in fluid catalytic cracking units	2.48
40	Plasma gasification of municipal solid waste	3.35	80	CO_2 capture in coal-fired thermoelectric plants	2.46

Table 9 Prioritized technologies with sector and subsector for the proposed selection methods

Selection methods[1]	*ORS*	*SES*	*SER*	*SSE*
Technologies[2]	Silviculture with native species for restoration (A-o)	Silviculture with native species for restoration (A-o)	Silviculture with native species for restoration (A-o)	Precision agriculture (A-a)
	Flex hybrid vehicles (T)	Satellite monitoring (A-o)	Satellite monitoring (A-o)	Genetic improvement in beef cattle (A-a)
	Use of agricultural and agro-industrial waste (W)	Mixed planting silviculture with exotic and native species (A-o)	Mixed planting silviculture with exotic and native species (A-o)	Silviculture with native species for restoration (A-o)
	Plug-in hybrid electric vehicles (T)	Precision forestry and silviculture (A-o)	Precision forestry and silviculture (A-o)	Satellite monitoring (A-o)
	Satellite monitoring (A-o)	Flex hybrid vehicles (T)	Forestry genetic engineering (A-o)	Mixed planting silviculture with exotic and native species (A-o)
	Mixed planting silviculture with exotic and native species (A-o)	Plug-in hybrid electric vehicles (T)	Precision agriculture (A-a)	Photovoltaic solar induction stoves (B)
	Ethanol fuel cell electric vehicles (T)	Industry 4.0 (I-t)	Flex hybrid vehicles (T)	Flex hybrid vehicles (T)
	Precision forestry and silviculture (A-o)	Alternative materials for cement (I-c)	Plug-in hybrid electric vehicles (T)	Plug-in hybrid electric vehicles (T)
	Floating solar power plants (E-p)	Floating solar power plants (E-p)	Industry 4.0 (I-t)	Industry 4.0 (I-t)
	Forestry genetic engineering (A-o)	Green diesel (E-b)	Alternative materials for cement (I-c)	Alternative materials for cement (I-c)
	Photovoltaic solar induction stoves (B)	Photovoltaic solar induction stoves (B)	Floating solar power plants (E-p)	Floating solar power plants (E-p)
	Precision agriculture (A-a)	Use of vinasse and other agricultural residues (W)	Use of agricultural and agro-industrial waste (W)	Use of agricultural and agro-industrial waste (W)

[1]ORS, ordinal selection; SES, sectoral equity selection, SER; sectoral emissions representativeness selection, SSE; sub-sectoral emissions representativeness selection. [2]Sector and sub-sector in parenthesis, upper case denotes the sector and lower case the sub-sector, when applicable. For the sectors: A, Afolu; B, buildings; E, energy; I, industry; T, transport; W, waste. For the sub-sectors: a, agriculture; o, other land uses; c, cement; q, chemical; i, iron and steel; t, transversal; og, oil and gas E&P; r, refining; p, power; b, biofuels

their mitigation potentials and costs. Hence, some other alternatives that might be interesting for the country's development (for instance, by generating jobs and income or fostering a digital transformation) might be excluded in this framework (Grubb et al. 2021). To overcome such a limitation, stakeholders were called to suggest the inclusion in the shortlist of other low-carbon technologies that were eventually excluded by the costs and potentials criteria but are particularly interesting for the country.

Having a previous database of mitigation technologies built from the robust results of IAMs was a considerable contribution to the Brazilian TNA and provided a different shape to the process in comparison to countries with no previous databases of mitigation options. It supported the identification of technologies for all key economic sectors, rather than only for previously prioritized sectors. This allowed for an economy-wide MCDA in which technologies are prioritized before the sectors, which may provide more information for the country's climate framework beyond the TNA project goals, as further discussed in the following sectors. This calls for the importance of connecting the TNA to other existing or ongoing climate-related efforts in the country, as highlighted by Haselip et al. (2015).

Complex databases for climate technology options and models for an integrated assessment of all sectors are generally available in developed countries (Hofman and van der Gaast 2019). However, their existence is not the reality for most developing countries, although there are some experiences of developing countries which have their own IAMs for guiding their own climate strategy, as is the case of Ecuador with its ELENA model (Villamar et al. 2021). Hence, countries that possess such tools might draw more insights from the Brazilian TNA experience for fine-tuning their strategies with a stakeholders-engaged MCDA, as proposed by Hofman and van der Gaast (2019). These might include not only countries which have their own IAMs but also countries with previous projects that involved somehow an effort to map climate technologies. This could be the case for new rounds of TNA studies, which could benefit from the inclusion of other sectors rather than the formerly prioritized in terms of the construction of a broader strategy.

5.2 Insights on the choice of criteria and technology scoring

The selection of criteria for assessing the technologies was based on features of the technology regarding the three technology dimensions (Nygaard and Hansen 2015) — hardware, software, and orgware — and the potential co-benefits they can provide. Considering the technology dimension is an important requirement, even referred to as a "challenge" (Nygaard and Hansen 2015), for climate technology development and transfer projects (Boldt et al. 2012; de Coninck and Sagar 2015b; Goldar et al. 2019), particularly for TNAs (Haselip et al. 2019). Co-benefits, on the other hand, are important aspects for assuring public acceptance and political support for mitigation technologies and policies, as is the case for actions that promote health benefits and improvements in air quality (West et al. 2013; Bustamante et al. 2014; Soria et al. 2015; Chapman et al. 2018; Amelung et al. 2019; Wang et al. 2020). In the Brazilian TNA, the criteria were organized in two levels for the MCDA (Fig. 3), and the first-level categories were determined as "technological", "physical", "socio-economic", and "institutional". Most of the reviewed TNAs for mitigation technologies (presented in Sect. 2.2) also used a two-level approach for the criteria. Yet, while most of them included criteria associated with co-benefits (such as "social", "environmental", and "economic"), only around one-third included "political" or "institutional" criteria, which indicates that the orgware dimension is usually underrepresented in such studies, as stated by Nygaard and Hansen (2015).

The SRRCs analysis aims to evaluate the quality of the choice of the sub-criteria for the Brazilian TNA, by testing the hypothesis of multiple accounts of one or more aspects when attributing scores to the technologies, evidenced by the existence of strong correlations between pairs of sub-criteria. As shown in Table 7, strong correlations were observed among the INT sub-criteria and between FP with WR, BD, and VC.

The rationale behind the choice of INT sub-criteria was to score the mitigation technologies on their alignment to the three main axes of policies and programmes that compose the portfolio of mitigation actions in Brazil. The other sub-criterion should reflect how the technologies fit in the current institutional environment, or basically whether it is likely to hamper or aid their development. Nevertheless, the alignment of a technology to a sectorial or national plan or climate policy usually considers the institutional environment. Hence, when a technology reaches a high score in an institutional sub-criterion, it is coherent that it is also highly scored in the others, which leads to strong correlations among the criteria. Thus, to avoid strong correlations, the INT sub-criteria representing alignment with public policies could have been grouped into a single sub-criterion. In addition, the IF sub-criterion could also have been broken down into elements that should be more independent between them such as regulatory/legal framework, access to funding and public acceptance.

The strong correlations observed for the FP sub-criterion are, likely, a repercussion of the water-food-energy-climate nexus in the technology scoring (WEF 2011). Since agriculture is the sector that globally accounts for more than 80% of water consumption (Hoff 2011), it is coherent that a positive impact on water availability also impacts positively food production. Otherwise, if a technology would require too much water to operate, it could negatively impact food production due to the eventual lack of water for irrigation. Regarding climate, technologies less resilient to climate change usually depend on renewable resources. Some of these technologies, especially in the energy sector, demand large portions of land and therefore compete with agriculture, imposing a negative impact on food production (Rasul and Sharma 2016). As for energy, the lack of strong correlations between the ER indicator and the others suggests that the technology score captured both synergies and trade-offs in the nexus with water, food, and climate.

There is an apparent contradiction between the goals of increasing agricultural production and conserving biodiversity. However, a strong positive correlation between the FP and BD sub-criteria was observed. This can be explained by the assumption that technologies that promote greater intensification of land use free up space for both increasing food production and new conservation areas. Notwithstanding, there are studies arguing that food production systems do not necessarily have to trade off with biodiversity (Chappell and LaValle 2011; Glamann et al. 2017), or even that biodiversity conservation is essential for ensuring food security (Frison et al. 2011).

Regarding the technology scoring process, as described in the “Methodology” section, technologies were assessed by the academic experts from the NCT and stakeholders were not involved in the process for avoiding biases. Yet, some limitations to that assumption should be acknowledged. First, an assessment of a high number of technologies with a large number of criteria requires an extensive review and each score is as robust as the number of evidence on which it is based (de Coninck et al. 2018). Hence, the robustness of this assessment is directly related to the amount of evidence reviewed and the fact that if no evidence on the relation of a technology to a criterion was found, this does not necessarily mean that there is no relation. Second, it is common that scientific literature disagrees on the performance of a technology in a criterion (de Coninck et al. 2018). An example of such a degree of uncertainty is that the mitigation costs of technologies are commonly informed in a range of US$/t of CO_2, which sometimes vary from negative to very high values (Borba et al. 2012; Fuss et al. 2018). Thus, the assignment of a performance score in such cases can be a subjective exercise for the experts' team. Third, the technology performance in the criteria can change over time, as is the case of the cost of renewable energy which fell more rapidly than the most optimistic learning curves considered in the modelled scenarios of the last decade (Grubb et al. 2021).

5.3 Insights on the application of the MCDA/AHP for weighting the criteria

The criteria weighting results are dependent on the space-temporal context in which the process is undertaken, as it relies on the current perception of individuals who participate in the survey (Ernst and van Riemsdijk 2013). Hence, even though it is essential that TNA studies are conducted through a participatory process (Hofman and van der Gaast 2019; Pandey et al. 2022), some caution must be taken to affirm that such a process actually represents society's preferences. Having participatory approaches is challenging in a complex country with a high level of inequalities such as Brazil (Cornwall and Shankland 2013). Therefore, there are limitations to the interpretation of the results that should be highlighted. First, a participative approach should not be mistaken for an inclusive process, therefore caution must be taken when calling the results representative of the Brazilian society's interests. Thus, as the survey is conducted with the participation of some high-level stakeholders in the country, its results are only representative of an average view of some representatives of groups of interest from the public and private sectors, civil society, and academia that are included in the discussions of climate in Brazil under the scope of the "Rede CLIMA". Moreover, most participants of the survey are from the public sector, especially from the Ministry of Science, Technology, and Innovations (Table 3), since not all the invited stakeholders responded to the survey. This limitation reflects the importance of the challenging task of engaging stakeholders in a TNA (Rogat 2015; Hofman and van der Gaast 2019).

Also, since the participatory process and the AHP methodology itself can have their consistency jeopardized by a lack of rationality in participants responses, it is important to conduct a consistency analysis of the resulting matrix of weights (Le Pira et al. 2015). In the case of TNA Brazil, all the matrices were consistent in the first round, so the survey process was not repeated. Another precaution taken in the present study to prevent eventual conflicts of interests and biases within the process was not to provide access for stakeholders to the scores given to the technologies in the shortlist. Additionally, to simplify the questions (and answers) in the questionaries, the scale of comparison was simplified from 17 (Saaty's scale in the AHP methodology) to 5 categories, to reduce psychological burden and inconsistency of judgement.

Regarding the AHP/MCDA result, the JI sub-criterion was given the highest weight in the analysis by stakeholders. Traditionally, countries of the Global South face more challenging scenarios in terms of unemployment and economic growth (WEF 2018), making these issues a local priority. Furthermore, Brazil is facing a major economic crisis since 2016 (Nunes and Melo 2017; IBGE 2020a), worsened in recent years by social and political associated crises (Rochedo et al. 2018; de Area Leão Pereira et al. 2019). Hence, a high and rising rate of unemployment has been observed in the country since 2014 (ILO 2018; IBGE 2020b), which probably explains in part why the JI sub-criterion was considered by stakeholders as the most valuable co-benefit associated with mitigation efforts. Still, the surveys were performed before the COVID-19 pandemic outbreak, which further aggravated the social and economic situation in the country (IMF 2020; Schwab and Zahidi 2020) and would certainly impact the participants` judgement probably by giving even more importance to the criterion.

The IF sub-criterion has reached almost the same weight within its group, under the INT criterion. This result reflects the relevant role of institutions in incentivizing technology development (WEF 2018; Teixeira et al. 2021). Moreover, despite the high-level capacity in the long-term modelling science, the Brazilian institutions are considered to be poorly prepared to foster a general environment of innovation and competitiveness vis-à-vis other countries (Schwab and Zahidi 2020). This means that institutional barriers can be a significant burden for the development of innovative technologies that are out of step with the current institutional framework. These aspects may have led stakeholders to consider the institutional framework sub-criterion more important than the other "Institutional" sub-criteria, which reflect the technologies' alignment to incentive policies and programmes.

In the "Physical" group, the most relevant sub-criterion was found to be the "Impacts on water availability". Even though Brazil has abundant water resources, these are concentrated mainly in low demographic density areas and the power system and agriculture sectors are very dependent on water (Lucena et al. 2018; Vasquez-Arroyo et al. 2020). According to EPE (2021), 65.2% of the Brazilian electricity mix was composed of hydropower plants in 2020. Additionally, the National Water Agency of Brazil points out that water for irrigation in agriculture and livestock accounted for 66.1% and 12.6% of the water consumption in Brazil, respectively (ANA 2019). Therefore, it is understandable that the stakeholders find it relevant to assess if the development of a mitigation technology can affect, positively or negatively, the Brazilian water resources.

Finally, within the "Technological" group of sub-criteria, the attribution of weights was more balanced. However, the three sub-criteria more inherently related to the technical performance of a technology were thought to be more important than the "VC" sub-criterion. Possibly because the latter is perceived as a long-term risk with an uncertain impact on the technology, while the others represent established parameters in technological assessments.

5.4 Insights on the ranking and prioritization process

The first positions in the final ranking were mainly occupied by technologies from the Afolu sector, particularly in the other land uses subsector. These technologies, in general, have a relatively low cost and high mitigation potential, bring several environmental co-benefits, such as environmental services, and are better suited to the Brazilian institutional framework (Bustamante et al. 2014; Deng et al. 2017; Rochedo et al. 2018). Therefore, they received good ratings on most of the sub-criteria and obtained high final values. This is also the case for the technologies related to the ethanol industry (hybrid flex vehicles, ethanol fuel cell electric vehicles, and use of agricultural and agro-industrial waste). These technologies were well rated in the socioeconomic indicators, since they have the potential to provide a high number of jobs (IRENA 2019), and show competitive advantages for Brazil, due to the large tradition in large-scale production of sugarcane ethanol (Goldemberg et al. 2004). On the other hand, technologies from the energy sector, which is generally considered a high priority sector for climate mitigation in TNAs (Nygaard and Hansen 2015; Puig et al. 2018; Hofman and van der Gaast 2019), were not much present in the first positions of the ranking. Perhaps this is because Brazil already has an energy mix with a relatively high share of renewables — 48.4% of renewables in 2020 compared to an average of 13.8% in the World and 11% in OECD countries (EPE 2021), which might enhance the cost and limit the potential of co-benefits for further mitigation in the sector.

Regarding the prioritization process, taking into consideration, just the simple ordinal ranking would privilege the Afolu and transport sectors over the others. That sort of concentration could lead to a non-desirable result for the TAP's implementation in Brazil. The privileged sector could become overwhelmed with too many technology development projects. Meanwhile, the other sectors that could be mobilized to develop promising technologies would not receive the necessary funding. Therefore, proposing alternative methods for selecting priority technologies from the ranking in a more balanced manner, together with the discussion with the TAC, enabled the results to include a more diverse set of interests.

On this topic, it is important to highlight the role of the TAC in the TNA Brazil project. The TAC represents an additional instance of follow-up, technical support, and decision-making in the TNA project in relation to the standard structure. Therefore, TAC plays a more active role in project execution compared to NSC. Hence, the existence of the TAC enables the use of a tailored method for selecting technologies from the MCDA's final ranking, which might be important for improving political buy-in for the TAP. Nonetheless, attributing the final decision power to the TAC can make the process vulnerable to political interests, particularly of ministerial members indicated by the government in place. The transparency of the process, therefore, is an important element to avoid this risk. In the case of the TNA Brazil project, the method used to provide transparency to the process was the appointment of TAC members by a Ministerial Ordinance (BRASIL 2019b).

The Brazilian TNA approach is an alternative to the sectoral prioritization frequently conducted in other TNA studies. In the referred approach, sectors or subsectors are prioritized and chosen according to their individual contribution to relevant criteria to the country (e.g. GDP or GHG emissions) before the identification and classification of the technologies. The comparison and ranking of technologies are performed exclusively within the same sector and only the best-ranked (sub-)sector(s) is(are) considered. This method disregards the real position of each sector's mitigation options in the overall national ranking. They may lead to the selection of technologies for the development of TAPs not for their own potential to meet national goals, but rather for the sector to which they belong. However, a general ranking is challenging since it requires the application of the same set of technological assessment criteria to all sectors. Hence, it limits the employment of sector-specific, yet relevant, criteria in the analysis, e.g. travel time to assess transport technologies.

Yet, the advantages of seeking a well-suited technology portfolio across sectors outweigh those limitations, especially in countries such as Brazil where a single sector (i.e. Afolu) tends to concentrate most of the emissions and mitigation opportunities. If the number of technologies per sector was divided linearly beforehand, it would have been left out highly promising Afolu technology while including technologies from sectors such as buildings and residues with a much lower mitigation potential. Moreover, if an early prioritization of sectors/sub-sectors had been conducted, the energy sector was likely to be given a higher relevance in the results than the one it obtained from the overall ranking, especially if the recommendation of choosing no more than three sectors (Hofman and van der Gaast 2019) was followed. In other words, a "one-size-fits-all" approach following strictly the TNA guidebook would have led to different results for the Brazilian TNA, probably less connected to the country's reality and actual needs. This calls for the importance of country-specificity (Busch et al. 2021) in the design of such technology development and transfer processes.

A final ranking containing technologies from all sectors provides an integrated and simultaneous view of the mitigation options across different sectors and sub-sectors. Thus, it delivers important information regarding the opportunities framework for innovation on mitigation technologies in the country, comprising all key sectors. Therefore, it promotes a solid foundation for the decision-making process on the sectoral distribution of technologies to be developed in the TAPs. But beyond the TNA project's original scope, such a comprehensive ranking, as well as the database generated by the technology scoring, is also a valuable co-product of the TNA. It provides a map of the country's technology needs and potential, which can be a useful information source for financing agents and developers to evaluate how technology development projects pose within the multi-sectoral environment for innovation in climate sound options in the country.

6 Final considerations

Technology innovation and development are paramount for reaching the global climate goals, which makes imperative the strengthening of developing countries' NSI for climate sound technologies. International technology transfer and cooperation mechanisms are intended to come in aid of that task, while their success depends on considering the national circumstances and needs of the recipient countries. Under this appeal, TNAs are an important tool for the identification and prioritization of climate technologies in developing countries, which should lead to the proposal of emblematic projects for priority sectoral technologies in the scope of a TAP. The need for country-driven approaches for TNAs is consistently mentioned in the knowledge body on the theme. However, the literature lacks discussions on country-specific processes for the TNA, as the methodology is usually referred to as a one-size-fits-all approach. For instance, although more than 80 countries already conducted TNA studies, no scientific paper was found discussing lessons learned from the application of a tailored TNA process for a specific country, shaped by its current capabilities in climate technologies.

Brazil is a developing country with exceptional capabilities in terms of modelling scenarios for supporting its climate strategy. Therefore, a Brazilian-tailored TNA study is particularly interesting, as it can integrate results from IAMs to a participatory MCDA. Thence, the experiences drawn from it may provide insights not only for future TNA studies in developing countries but also for country-specific processes of climate technologies prioritization in general, as for the case of developed countries willing to fine-tune their IAM scenario-based climate strategies with a participatory MCDA. Hence, this study presents lessons learned from the identification and prioritization step of a TNA for mitigation technologies in Brazil, which applied an MCDA analysis and a selection of priority technologies tailored to the climate context of the country.

Participatory approaches are very relevant for TNAs, as stated by many authors. Nonetheless, there is a need for caution in considering the participatory process inclusive or, even further, representative of the view of the society. The stakeholders invited to participate in the MCDA criteria-weighting survey, although aligned to a network of high-level discussions on climate technology in Brazil, are representative of a political and economic elite in the country and are geographically concentrated in the rich Center-South region of Brazil. Future studies may address this issue by including a broader set of socially and geographically diverse stakeholders, for assessing how specific social groups or sub-national priorities for climate technology development and transfer compare to the country's average. A future TNA study for Brazil focused on technologies for adapting to climate change could also be interesting to compose the country's climate action portfolio on this other front.

The final ranking containing technologies from the Brazilian key sectors is an important result because it provides decision and policymakers with an integrated and simultaneous view of the mitigation options across different sectors and sub-sectors. This result can better support a tailored selection of technologies to be developed in the TAPs by the TAC, assuring more political support and financial viability for the development of projects for the core technologies group in the country. Nevertheless, attributing the final decision to the TAC may imply a risk that members of ministries conduct the final selection of technologies to privilege sectors aligned with the agenda of the government in place. Beyond the TNA project's scope, an overall ranking is an important co-product of the TNA, as it works as an economy-wide map of technology needs and potentials. This is also the case of the technologies scoring database, which would benefit from becoming a public document with periodic updates and the inclusion of a robustness analysis.

Finally, if a one-size-fits-all approach had been conducted for the Brazilian TNA, certainly other results would have been obtained, probably less connected to the country's context of NIS capability and its actual needs. This calls for the importance that a technology transfer project such as a TNA must not only be country-driven but also the methodology itself should be reinterpreted and adapted through a country-specific approach, as this is at the root of the innovation concept. We call for other countries that conduct technology transfer processes such as TNAs not to uncritically apply one-size-fits-all methodologies but to propose adaptations that make sense to their context and then write about their experiences. We do not claim that the Brazilian TNA methodology is better than the standard procedure, but rather that it is more adequate to the Brazilian context. We claim that countries should use the TNA guidebook for support rather than for illumination.

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References

ANA (2019) Conjuntura Recursos Hídricos Brasil - Informe Anual. In: Agência Nac. Águas. https://www.snirh.gov.br/portal/centrais-de-conteudos/conjuntura-dos-recursos-hidricos/conjuntura_informe_anual_2019-versao_web-0212-1.pdf

Acosta M, Corral S (2017) Multicriteria decision analysis and participatory decision support systems in forest management. Forests 8:116. https://doi.org/10.3390/f8040116

Amelung D, Fischer H, Herrmann A et al (2019) Human health as a motivator for climate change mitigation: results from four European high-income countries. Glob Environ Chang 57:101918. https://doi.org/10.1016/j.gloenvcha.2019.05.002

Borba BSMC, Lucena AFP, Rathmann R et al (2012) Energy-related climate change mitigation in Brazil: potential, abatement costs and associated policies. Energy Pol 49:430–441. https://doi.org/10.1016/j.enpol.2012.06.040

Boyd A (2012) Informing international UNFCCC technology mechanisms from the ground up: Using biogas technology in South Africa as a case study to evaluate the usefulness of potential elements of an international technology agreement in the UNFCCC negotiations process. Energy Pol 51:301–311. https://doi.org/10.1016/j.enpol.2012.08.020

Busch PO, Feil H, Heinzel M et al (2021) Policy recommendations of international bureaucracies: the importance of country-specificity. Int Rev Adm Sci 87:775–793. https://doi.org/10.1177/00208523211013385

Bustamante M, Robledo-Abad C, Harper R et al (2014) Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. Glob Chang Biol 20:3270–3290. https://doi.org/10.1111/gcb.12591

Boldt J, Nygaard I, Hansen UE, Trærup SLM (2012) Overcoming barriers to the transfer and diffusion of climate technologies. UNEP Risø Centre on Energy, Climate and Sustainable Development, Risø DTU National Laboratory for Sustainable Energy

BRASIL (2008) Plano Nacional sobre Mudança do Clima - PNMC. In: Com. Interministerial sobre Mudança do Clima. https://antigo.mma.gov.br/estruturas/smcq_climaticas/_arquivos/plano_nacional_mudanca_clima.pdf

Brasil. Ministério da Agricultura, Pecuária e Abastecimento. Plano setorial de mitigação e de adaptação às mudanças climáticas para a consolidação de uma economia de baixa emissão de carbono na agricultura : plano ABC (Agricultura de Baixa Emissão de Carbono) / Ministério da Agricultura, Pecuária e Abastecimento, Ministério do Desenvolvimento Agrário, coordenação da Casa Civil da Presidência da República.–Brasília: MAPA/ACS, 2012. 173 p. ISBN 978-85-7991-062-0

BRASIL (2015) Intended nationally determined contribution towards achieving the objective of the united nations framework convention on climate change. United Nations Framework Convention on Climate Change

BRASIL (2017) Estimativas anuais de emissões de gases de efeito estufa no Brasil. Brasília: Ministério da Ciência, Tecnologia Inovações e Comunicações. https://sirene.mctic.gov.br/portal/export/sites/sirene/backend/galeria/arquivos/2018/10/11/Estimativas_4ed.pdf

BRASIL (2019a) Ministério da Ciência, Tecnologia, Inovações e Comunicações. Gabinete do Ministro. PORTARIA No 1.631, DE 1° DE ABRIL DE 2019a. Institui o Comitê Técnico Consultivo do Projeto "Avaliação das Necessidades Tecnológicas para Implementação de Planos de Ação Climática no Brasil". Diário Oficial da União, Brasília

BRASIL (2019b) Ministério da Ciência, Tecnologia, Inovações e Comunicações. Gabinete do Ministro. PORTARIA No 3.008, DE 19 DE JUNHO DE 2019a. Diário Oficial da União, Brasília

BRASIL (2019c) Presidência da República. Secretaria-Geral. Subchefia para Assuntos Jurídicos. DECRETO Nº 9.888 DE 27 DE JUNHO DE 2019. Dispõe sobre a definição das metas compulsórias anuais de redução de emissões de gases causadores do efeito estufa para a comercialização de combustíveis de que trata a Lei nº 13.576, de 26 de dezembro de 2017, e institui o Comitê da Política Nacional de Biocombustíveis - Comitê RenovaBio. Diário Oficial da União, Brasília

Byrne R, Schoots K, Watson J, Ockwell D, de Coninck H, Gallagher KS, Sagar A (2012) Innovation systems in developing countries. Climate Strategies Policy Brief in Climate Technology and Development project. https://www.climatestrategies.org

Chapman AJ, McLellan BC, Tezuka T (2018) Prioritizing mitigation efforts considering co-benefits, equity and energy justice: fossil fuel to renewable energy transition pathways. Appl Energy 219:187–198. https://doi.org/10.1016/j.apenergy.2018.03.054

Chappell MJ, LaValle LA (2011) Food security and biodiversity: can we have both? An agroecological analysis. Agric Human Values 28:3–26. https://doi.org/10.1007/s10460-009-9251-4

Cornwall A, Shankland A (2013) Cultures of politics, spaces of power: contextualizing Brazilian experiences of participation. J Polit Power 6:309–333. https://doi.org/10.1080/2158379X.2013.811859

Colombia (2013) Evaluación De Necesidades Tecnológicas Y Planes De Acción Tecnológica Para Mitigacion Al Cambio Climático. In: Technol. Needs Assess. https://tech-action.unepdtu.org/wp-content/uploads/sites/2/2013/12/informeent-mitigacion-colombia-13.pdf

da Silva FTF, Carvalho FM, Corrêa JLG et al (2018) CO2 capture in ethanol distilleries in Brazil: designing the optimum carbon transportation network by integrating hubs, pipelines and trucks. Int J Greenh Gas Control 71:168–183. https://doi.org/10.1016/j.ijggc.2018.02.018

de Coninck H, Puig D (2015) Assessing climate change mitigation technology interventions by international institutions. Clim Change 131:417–433. https://doi.org/10.1007/s10584-015-1344-z

de Coninck H, Sagar A (2015b) Making sense of policy for climate technology development and transfer. Clim Policy 15:1–11. https://doi.org/10.1080/14693062.2014.953909

de Area Leão Pereira EJ, de Silveira Ferreira PJ, de Santana Ribeiro LC et al (2019) Policy in Brazil (2016–2019) threaten conservation of the Amazon rainforest. Environ Sci Policy 100:8–12. https://doi.org/10.1016/j.envsci.2019.06.001

De Luca S (2014) Public engagement in strategic transportation planning: an analytic hierarchy process based approach. Transp Policy 33:110–124. https://doi.org/10.1016/j.tranpol.2014.03.002

Deng HM, Liang QM, Liu LJ, Anadon LD (2017) Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. Environ Res Lett 12:123001. https://doi.org/10.1088/1748-9326/aa98d2

Doyle JR, Green RH, Bottomley PA (1997) Judging relative importance: direct rating and point allocation are not equivalent. Organ Behav Hum Decis Process 70:65–72. https://doi.org/10.1006/obhd.1997.2694

de Coninck H, Sagar A (2015) Technology in the 2015 Paris Climate Agreement and beyond. ICTSD Programme on Innovation, Technology and Intellectual Property. Issue Paper No. 42. International Centre for Trade and Sustainable Development, Geneva, Switzerland, wwwictsd.org

de Coninck H, Revi A, Babiker M et al (2018) Strengthening and implementing the global response. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,. Cambridge University Press, Geneva, pp 313–444

Ernst KM, van Riemsdijk M (2013) Climate change scenario planning in Alaska's National Parks: Stakeholder involvement in the decision-making process. Appl Geogr 45:22–28. https://doi.org/10.1016/j.apgeog.2013.08.004

Estévez RA, Espinoza V, Ponce Oliva RD et al (2021) Multi-criteria decision analysis for renewable energies: research trends, gaps and the challenge of improving participation. Sustain 13:3515. https://doi.org/10.3390/su13063515

EPE (2021) Brazilian Energy Balance: summary report 2021 - reference year 2020. Empresa de Pesquisa Energética: Rio de Janeiro, Brazil.

Frison EA, Cherfas J, Hodgkin T (2011) Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. Sustainability 3:238–253. https://doi.org/10.3390/su3010238

Fuss S, Lamb WF, Callaghan MW et al (2018) Negative emissions—part 2: costs, potentials and side effects. Environ Res Lett 13:063002. https://doi.org/10.1088/1748-9326/aabf9f
Fagerberg J (2006) ' Innovation: A Guide to the Literature', in Jan Fagerberg, and David C. Mowery (eds), The Oxford Handbook of Innovation (2006; online edn, Oxford Academic, 2 Sept. 2009), https://doi.org/10.1093/oxfordhb/9780199286805.003.0001.
Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Policy 31:1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8
Geels FW (2014) Reconceptualising the co-evolution of firms-in-industries and their environments: developing an inter-disciplinary Triple Embeddedness Framework. Res Policy 43:261–277. https://doi.org/10.1016/j.respol.2013.10.006
Glamann J, Hanspach J, Abson DJ et al (2017) The intersection of food security and biodiversity conservation: a review. Reg Environ Chang 17:1303–1313. https://doi.org/10.1007/s10113-015-0873-3
Goldemberg J, Coelho ST, Nastari PM, Lucon O (2004) Ethanol learning curve - the Brazilian experience. Biomass Bioenerg 26:301–304. https://doi.org/10.1016/S0961-9534(03)00125-9
Grubb M, Drummond P, Mercure J-F et al (2021) The new economics of innovation and transition: evaluating opportunities and risks. Economics of Energy Innovation and System Transition (EEIST), Exeter, UK
Goldar A, Sharma S, Sawant V, Jain S (2019) Climate change & technology transfer – barriers, technologies and mechanisms. Working Paper, No. 382, Indian Council for Research on International Economic Relations, New Delhi, India
Höfer T, Sunak Y, Siddique H, Madlener R (2016) Wind farm siting using a spatial analytic hierarchy process approach: a case study of the Städteregion Aachen. Appl Energy 163:222–243. https://doi.org/10.1016/j.apenergy.2015.10.138
Hofman E, van der Gaast W (2019) Enhancing ambition levels in nationally determined contributions—learning from Technology Needs Assessments. Wiley Interdiscip Rev Energy Environ 8:1–15. https://doi.org/10.1002/wene.311
Haselip JA, Narkeviciute R, Rogat-Castillo JE, et al (2015) A step-by-step guide for countries conducting a Technology Needs Assessment, 1st edn. UNEP DTU Partnership, Copenhagen, Denmark
Haselip J, Narkeviciute R, Rogat J, Trærup S (2019) TNA step by step: a guidebook for countries conducting a Technology Needs Assessment and Action Plan, 2nd edn. UNEP DTU Partnership, Copenhagen, Denmark
Hoff H (2011) Understanding the nexus. In: Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute (SEI), Stockholm, pp 1–52
IMF (2020) Mitigating climate change—growth- and distribution-friendly strategies. In: World Economic Outlook: A Long and Difficult Ascent. (2020) Washington, DC
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.
IBGE (2020a) System of Quarterly National Accounts - SCNT. In: Inst. Bras. Geogr. e Estatística - Natl. Accounts. https://www.ibge.gov.br/en/statistics/economic/national-accounts/17262-quarterly-national-accounts.html?=&t=publicacoes.
IBGE (2020b) Continuous national household sample survey - continuous PNAD. In: Inst. Bras. Geogr. e Estatística - Stat. /Soc./Labor. https://www.ibge.gov.br/en/statistics/social/labor/16809-quarterly-dissemination-pnad2.html?=&t=o-que-e.
IRENA (2019) Renewable energy and jobs: annual review 2019. In: Int Renew Energy Agency. http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuid=36&CatID=141&SubcatID=585
ILO (2018) 2018 labour overview: Latin America and the Caribbean. In: Int Labour Organ Off Lat Am Caribb https://www.ilo.org/wcmsp5/groups/public/---americas/---ro-lima/documents/publication/wcms_675285.pdf
Jenkins J, Mansur S (2011) Bridging the clean energy valleys of death. In: Breakthr Inst https://s3.us-east-2.amazonaws.com/uploads.thebreakthrough.org/legacy/blog/Valleys_of_Death.pdf
Kou G, Lu Y, Peng Y, Shi Y (2012) Evaluation of classification algorithms using MCDM and rank correlation. Int J Inf Technol Decis Mak 11:197–225. https://doi.org/10.1142/S0219622012500095
Le Pira M, Inturri G, Ignaccolo M, Pluchino A (2015) Analysis of AHP methods and the Pairwise Majority Rule (PMR) for collective preference rankings of sustainable mobility solutions. Transp Res Procedia 10:777–787. https://doi.org/10.1016/j.trpro.2015.09.031
Liu H, Liang X (2011) Strategy for promoting low-carbon technology transfer to developing countries: the case of CCS. Energy Policy 39:3106–3116. https://doi.org/10.1016/j.enpol.2011.02.051

Lucena AFP, Hejazi M, Vasquez-Arroyo E et al (2018) Interactions between climate change mitigation and adaptation: the case of hydropower in Brazil. Energy 164:1161–1177. https://doi.org/10.1016/j.energy.2018.09.005

Marttunen M, Lienert J, Belton V (2017) Structuring problems for multi-criteria decision analysis in practice: a literature review of method combinations. Eur J Oper Res 263:1–17. https://doi.org/10.1016/j.ejor.2017.04.041

Nunes F, Melo CR (2017) Impeachment, political crisis and democracy in Brazil. Rev Cienc Política 37:281–304. https://doi.org/10.4067/s0718-090x2017000200281

Nygaard I, Hansen UE (2015) The conceptual and practical challenges to technology categorisation in the preparation of technology needs assessments. Clim Change 131:371–385. https://doi.org/10.1007/s10584-015-1367-5

Njie M (2017) Climate change mitigation technologies in the Gambian energy , transport and waste sectors. In: Technol. Needs Assess. https://tech-action.unepdtu.org/wp-content/uploads/sites/2/2019/03/mitigation-tna-report-finalreport-myversion11.pdf

Ockwell D, Byrne R (2016) Improving technology transfer through national systems of innovation: climate relevant innovation-system builders (CRIBs). Clim Policy 16:836–854

Olsen OE, Engen OA (2007) Technological change as a trade-off between social construction and technological paradigms. Technol Soc 29:456–468. https://doi.org/10.1016/j.techsoc.2007.08.006

Pandey N, Coninck H, Sagar AD (2022) Beyond technology transfer: innovation cooperation to advance sustainable development in developing countries. Wires Energy Environ 11:1–25. https://doi.org/10.1002/wene.422

Prasad RS, Sud R (2021) The pivotal role of UNFCCC in the international climate policy landscape: a developing country perspective. Glob Aff 7:67–78. https://doi.org/10.1080/23340460.2021.1912628

Puig D, Haselip JA, Bakhtiari F (2018) The mismatch between the in-country determinants of technology transfer, and the scope of technology transfer initiatives under the United Nations Framework Convention on Climate Change. Int Environ Agreements Polit Law Econ 18:659–669. https://doi.org/10.1007/s10784-018-9405-1

PMR (2018) Comentários e sugestões: fase de diagnósticos setoriais - Projeto PMR Brasil. In: Proj PMR Bras http://gvces.com.br/comentarios-e-sugestoes-fase-de-diagnosticos-setoriais-projeto-pmr-brasil/?locale=pt-br

Rasul G, Sharma B (2016) The nexus approach to water–energy–food security: an option for adaptation to climate change. Clim Policy 16:682–702. https://doi.org/10.1080/14693062.2015.1029865

Rissman J, Bataille C, Masanet E et al (2020) Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070. Appl Energy 266:114848. https://doi.org/10.1016/j.apenergy.2020.114848

Rochedo PRR, Soares-Filho B, Schaeffer R et al (2018) The threat of political bargaining to climate mitigation in Brazil. Nat Clim Chang 8:695–698. https://doi.org/10.1038/s41558-018-0213-y

Rogat J (2015) Identification and engagement of stakeholders in the TNA process a guide for national TNA teams. UNEP DTU Partnership, Copenhagen

Rathmann R (2017) Modelagem integrada e impactos econômicos de opções setoriais de baixo carbono. Ministério da Ciência, Tecnologia, Inovação e Comunicação: Brasília, Brazil

Rathmann R, Schaeffer R, Rajão R et al (2021) Report on the technology needs assessment for the implementation of climate action plans in Brazil: mitigation. In: Minist. Sci Technol Innov United Nations Environ Program. https://sirene.mctic.gov.br/portal/export/sites/sirene/backend/galeria/arquivos/2021/05/20/1.-TNA-report-mitigation.pdf

Saaty RW (1987) The analytic hierarchy process-what it is and how it is used. Math Model 9:161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Şahin M (2021) A comprehensive analysis of weighting and multicriteria methods in the context of sustainable energy. Int J Environ Sci Technol 18:1591–1616. https://doi.org/10.1007/s13762-020-02922-7

Soria R, Portugal-Pereira J, Szklo A et al (2015) Hybrid concentrated solar power (CSP)-biomass plants in a semiarid region: a strategy for CSP deployment in Brazil. Energy Policy 86:57–72. https://doi.org/10.1016/j.enpol.2015.06.028

Sagar A (2009) Technology development and transfer to meet climate and developmental challenges. In: Delhi High Level Conference on Climate Change: Technology Development and Transfer. United Nations Department of Economic and Social Affairs, New Delhi

Schwab K, Zahidi S (2020) The global competitiveness report: how countries are performing on the road to recovery. In: World Econ. Forum. https://www3.weforum.org/docs/WEF_TheGlobalCompetitivenessReport2020.pdf

Tagomori IS, Carvalho FM, da Silva FTF et al (2018) Designing an optimum carbon capture and transportation network by integrating ethanol distilleries with fossil-fuel processing plants in Brazil. Int J Greenh Gas Control 68:112–127. https://doi.org/10.1016/j.ijggc.2017.10.013
Teixeira A, Cristo-Andrade S, Mainardes EW (2021) Internal barriers for the Brazilian economy to achieve external competitiveness. In: Ferreira JJM, Teixeira SJ, Rammal HG (eds) Technological Innovation and International Competitiveness for Business Growth: Challenges and Opportunities. Springer International Publishing, Cham, pp 119–140
Trærup S, Bakkegaard RK (2015) Evaluating and prioritizing technologies for adaptation to climate change. In: UNEP DTU Partnersh. https://backend.orbit.dtu.dk/ws/portalfiles/portal/117917558/Evaluating_and_prioritizing.pdf
Ürge-Vorsatz D, Herrero ST, Dubash NK, Lecocq F (2014) Measuring the co-benefits of climate change mitigation. Annu Rev Environ Resour 39:549–582. https://doi.org/10.1146/annurev-environ-031312-125456
UN (2020) About the sustainable development goals. In: United Nations Sustain. Dev. https://www.un.org/sustainabledevelopment/sustainable-development-goals/.
UNEP DTU (2020) Technology Needs Assessment project. In: Technol. Needs Assess. https://tech-action.unepdtu.org/the-project/
UNEP DTU (2021) Technology Needs Assessment. In: TNA. https://tech-action.unepdtu.org/
UNFCCC (2016) Implementation of technology action plans of developing countries. In: United Nations Framew Conv Clim Chang http://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/TNA_HAB_infobox_2/3ff7e92c99774c2a91bc79052d2fa135/c7df29418ed74f638f54bb136d6cc968.pdf
van Til J, Groothuis-Oudshoorn C, Lieferink M et al (2014) Does technique matter; a pilot study exploring weighting techniques for a multi-criteria decision support framework. Cost Eff Resour Alloc 12:1–11. https://doi.org/10.1186/1478-7547-12-22
Vasquez-Arroyo E, Gandelman DA, da Silva F et al (2020) Implications of climate change impacts for the Brazilian electricity mix. Sustentabilidade Debate 11:122–138. https://doi.org/10.18472/SustDeb.v11n3.2020.33998
Villamar D, Soria R, Rochedo P et al (2021) Long-term deep decarbonisation pathways for Ecuador: insights from an integrated assessment model. Energy Strateg Rev 35:100637. https://doi.org/10.1016/j.esr.2021.100637
Vinhoza A, Schaeffer R (2021) Brazil's offshore wind energy potential assessment based on a spatial multi-criteria decision analysis. Renew Sustain Energy Rev 146:111185. https://doi.org/10.1016/j.rser.2021.111185
Wang T, Jiang Z, Zhao B et al (2020) Health co-benefits of achieving sustainable net-zero greenhouse gas emissions in California. Nat Sustain 3:597–605. https://doi.org/10.1038/s41893-020-0520-y
WEF (2011) Water security: the water-food-energy-climate nexus: the World Economic Forum water initiative. In: Isl. Press. http://choicereviews.org/review/https://doi.org/10.5860/CHOICE.49-1001
West JJ, Smith SJ, Silva RA et al (2013) Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. Nat Clim Chang 3:885–889. https://doi.org/10.1038/nclimate2009
WEF (2018) Benchmarking competitiveness in the fourth industrial revolution : introducing the global competitiveness. In: The Global Competitiveness Report. pp 37–47
Zavadskas EK, Vilutiene T (2006) A multiple criteria evaluation of multi-family apartment block's maintenance contractors: I - model for maintenance contractor evaluation and the determination of its selection criteria. Build Environ 41:621–632. https://doi.org/10.1016/j.buildenv.2005.02.019

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