Mitig Adapt Strateg Glob Change (2023) 28:19
https://doi.org/10.1007/s11027-023-10053-w

ORIGINAL ARTICLE

Exploring long-term mitigation pathways for a net zero Tajikistan

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Received: 4 May 2022 / Accepted: 22 February 2023 / Published online: 24 March 2023

Abstract

The Paris Agreement encourages Parties to prepare and submit long-term low greenhouse gas emission development strategies (LT-LEDS) to the United Framework Convention on Climate Change (UNFCCC). LT-LEDS are national strategies that identify pathways or scenarios for low-emission development to reach a long-term vision and/or target, while considering broader socio-economic goals. The development of a LT-LEDS is a national process, driven by national priorities and goals, with each country facing different obstacles, and requiring distinctive approaches, priorities, and actions for the required transformation. In this work, a novel five-step back-casting approach is developed to assess alternative mitigation pathways for Tajikistan in order to achieve carbon neutrality by 2050, presenting an initial assessment and mapping, and providing the country with a starting point for LT-LEDS development. The approach is based around a set of variables of policy interest, which are areas in which climate mitigation policies, actions, or programmes of incentives can be designed and implemented. Major strengths of the approach are the consistency with the Nationally Determined Contribution (NDC) and the national greenhouse gas (GHG) emission inventory. Four mitigation pathways are defined for Tajikistan, each incorporating different policy intensity levels for the variables of policy interest. It is found that although each of the four mitigation pathways provides a significant GHG emission reduction potential, only one reaches carbon neutrality by 2050, namely, the pathway that focusses on considerable policy efforts in all sectors of the economy and incorporates intensive policy efforts for both nature-based and technological carbon dioxide (CO_2) removal.

Keywords Long-term strategy · Back-casting · Tajikistan · Mitigation · Paris agreement · Net zero

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1 Introduction

Considering the United Nations Framework Convention on Climate Change (UNFCCC) objective to limit global warming to well below 2 °C above pre-industrial levels (1850–1900) and preferably to 1.5 °C (UNFCCC 2015), article 4, paragraph 19 of the Paris Agreement encourages Parties to prepare and submit long-term low greenhouse gas emission development strategies (LT-LEDS) to the UNFCCC. At the 2021 United Nations Conference of the Parties (COP26) in Glasgow, Parties agreed on the Glasgow Climate Pact, which urges Parties who have not yet done so to communicate a LT-LEDS by the next COP in Egypt in late 2022 (UNFCCC 2021a). LT-LEDS are voluntary long-term national strategies that identify nationally appropriate low-emission pathways or scenarios to 2050 while considering broader socio-economic goals, which are key tools to explore solutions for climate change mitigation, and analyse how decisions and actions taken today could affect long-term sustainable development. They aim to ensure coherent short-term climate action with long-term goals, support governments in policy alignment, increase stakeholder participation in low-emission development, improve the credibility of international commitments, and help attract international support (Falduto and Rocha 2020). LT-LEDS are a key element for countries to identify and set a long-term vision and/or target that defines a roadmap for economy-wide transformations needed to achieve low-emission development. These strategies are necessary as current international efforts are expected to fall short of meeting the global long-term temperature goal set by the Paris Agreement (UNFCCC 2021b).

In the context of limiting global warming to well below 2 °C and preferably 1.5 °C under the Paris Agreement, several countries have investigated their carbon neutral pathways within these objectives (Duan et al. 2021; Sugiyama et al. 2019; Kim et al. 2022), and more than five dozen countries have already submitted a long-term strategy to the UNFCCC, of which 28 developed countries and 28 developing countries (UNFCCC 2021c). As the development of an LT-LEDS is a national process, driven by national priorities and goals, each country will face different obstacles, and will require distinctive approaches, priorities, and actions for the required transformation, and as such, the LT-LEDS process is flexible and unique to each nation. Thus, as there is not one internationally agreed methodology, several studies have investigated mid-century mitigation options for countries both at the national level (Fujino et al. 2008; Delgado et al. 2020; La Rovere et al. 2018) and at the sub-national level (Hussain et al. 2021; Naegler et al. 2021; Zhang et al. 2020), incorporating a variety of approaches and models to assess the most favourable pathways. For instance, Fujino et al. quantified two scenarios to 2050 using several socio-economic models, namely, a population and household model (PHM), a building dynamics model (BDM), a transportation demand model (TDM), and a computable general equilibrium (CGE)), but did not ensure consistency with the Nationally Determined Contribution (NDC) and the national greenhouse gas (GHG) emission inventory of Japan (Fujino et al. 2008). Delgado et al. developed three long-term decarbonisation scenarios to 2050 using the Global Change Analysis Model (GCAM) with one scenario reflecting Colombia’s NDC. However, rather than analysing and prescribing policy instruments relevant to the national circumstances of the country and linking the scenarios to the feasibility of these policy instruments, the approach links the scenarios to Colombia’s commitments under the Paris Agreements global warming goals (Delgado et al. 2020). As such, each of these studies are based on different methods, and consider a wide range of assumptions on technological, societal, and other developments. Scientists and modellers therefore need to apply unique options and hypotheses when developing LT-LEDS (Ourbak and Tubiana 2017), considering the national circumstances of the country.

However, there has been limited research in the area of carbon neutrality for Tajikistan, and although Tajikistan has adopted long- and medium-term development strategies, the country is lacking an overarching strategy defining the country's low-emission development objectives to 2050 in the context of the Paris Agreement, and against which shorter-term documents could be benchmarked. These defined hierarchies, where long-term documents descend through medium- and short-term documents, allow the programmes and actions of these shorter-term strategies to be linked with longer-term objectives and goals. This would support Tajikistan in weighing the costs and benefits of policy decisions and infrastructure development options, and could benefit the country in avoiding costly and unsustainable development pathways.

This work assesses alternative mitigation pathways for Tajikistan to achieve carbon neutrality by 2050, implying reaching net-zero GHG emissions by balancing emissions with removals. It builds on existing studies and guidance of developing LT-LEDS, adjusted to the unique national circumstances and the country goals, and linked to Tajikistan's NDC and national GHG emission inventory. The study provides key insights to support Tajikistan in setting its 2050 vision for climate neutrality by assessing all key emitting sectors and exploring pathways to achieve the transition, and can be considered the base version or starting point for LT-LEDS development (Hans et al. 2020). Furthermore, this work contributes to the existing literature by providing a robust methodological approach for the development of LT-LEDS, supporting the international community in reaching the goals of the Paris Agreement.

The paper is structured as follows. In Sect. 2, background information is provided on the LT-LEDS concepts relevant to the approach of this work and the current emission profile of the country. Section 3 introduces the methodology following the developed five-step back-casting approach, before the results and discussion are presented in Sect. 4. Finally, in Sect. 5, the conclusions of the paper are discussed, outlining the main takeaways from the work, and avenues for future work.

2 Background and related work

2.1 Goal setting and development of LT-LEDS

LT-LEDS rely on the development of certain scenarios for low-emission development. These scenarios do not provide concrete predictions, but rather describe possible future developments related to a set of boundaries or conditions. However, there are different types of scenarios depending on the objective of the research. Firstly, there is a clear distinction between descriptive and normative scenarios. Descriptive scenarios do not specify a desired outcome for the identified events, whereas normative scenarios do describe possible pathways to a certain goal, such as reducing GHG emissions, and are the type of scenarios considered in LT-LEDS development (Naegler et al. 2021). Furthermore, a classification can be made between forecasting and back-casting scenarios. While forecasting approaches base their projections on assumptions from the present situation and observed trends to analyse what is likely going to happen, back-casting approaches analyse possibilities to reach specified outcomes in the future (Chang et al. 2021; Bendor et al. 2021). This approach is particularly effective for sustainable planning as it supports a systematic and coordinated method for handling complex issues and considers solutions for current trends that are part of the problem to be solved

(Holmberg and Robert 2011), with long-term mitigation pathways generally following this method to assess whether the mitigation goals and objectives in a given time frame are technically and financially feasible.

For the development of forecasted mitigation scenarios, two main modelling approaches can be identified. Firstly, macro-economic top-down modelling approaches analyse the economy as a whole and focus on each of the economic variables such as population, economic growth, and energy intensity to explore solutions for limiting carbon dioxide (CO_2) emissions (Nguyen et al. 2021a, b). The technological bottom-up modelling approach instead focusses on technological options or project-specific mitigation policies, and often does not consider the full macro-economic framework (Zhang et al. 2020; Fortes et al. 2013). As part of these approaches, a 'benchmark' scenario is required against which the impact of the developed mitigation scenarios can be assessed. Several studies (Teng and Xu 2012; Roberts et al. 2019) express problems in the misuse of terms such as business-as-usual scenario, baseline scenario, and reference scenario, with both developed and developing countries using these terms and their underlying assumptions inconsistently in their application. It is therefore essential that when using one of these terms in research or policy documents, a clear definition is provided on the specific policies and measures that are considered in the scenario to avoid any confusion and ambiguity (Teng and Xu 2012).

These climate modelling approaches generate policy and cost-optimised scenarios adapted to country-specific circumstances to realise alternative climate change conditions that limit global warming. However, it is important to note that the Intergovernmental Panel on Climate Change (IPCC) states that all the considered pathways to limit global warming to 1.5 °C integrate the use of carbon dioxide removal (CDR) (IPCC 2018), with 86% of all the IPCC's scenarios that have a 50% chance of limiting global warming to below 2 °C also assuming the adoption of negative emission technologies (Anderson 2015). Multiple studies therefore highlight CDR as a necessity for achieving the climate goals of the Paris Agreement, as without its incorporation, nations will be required to pursue higher GHG reduction rates than what is currently deemed feasible in the given timeframe (Buylova et al. 2021; Holz et al. 2018; Sinha and Chaturvedi 2019). CDR thus plays an integral role in countries' LT-LEDS to achieve net-zero emissions by the mid-century.

Another key obstacle for policymakers to overcome when developing an LT-LEDS is the assessment of the associated abatement costs related to certain emission reductions. Marginal abatement cost (MAC) curves have become one of the most important tools for analysing the cost-effectiveness of climate mitigation policies (Kesicki and Ekins 2012; Jiang et al. 2019). A MAC curve is a graph that depicts the costs in a given currency, usually in United States dollars (USD), for reducing one unit of pollution, generally in million tonnes of CO_2, which supports the identification of the most cost-efficient options to achieve a certain target (Kesicki and Strachan 2011). Negative MAC values mean that the introduction of new technologies leads to lower emissions and to a financial advantage, as these less expensive processes and technologies will lead to the avoidance of costs in the long term (Wächter 2013). MAC curves have been applied at different levels of society in assessing the economics associated with climate change mitigation, from the national level, such as in Brazil (Vogt-Schilb et al. 2014) and China (Wang et al. 2011), to the subnational level, such as Sao Paulo in Brazil (Souza et al. 2018), as well as for non-CO_2 GHG emissions (Anderson and Morgenstern 2011) and for specific sectors, such as the building sector in Armenia and Georgia (Timilsina et al. 2016). Many governments and entities therefore rely on this analytical approach to support the selection of financially favourable GHG mitigation measures according to national circumstances.

2.2 Emission profile of Tajikistan

The latest national GHG emission inventory of Tajikistan (UNFCCC 2021d) provides the GHG emissions of the country for the period 1990–2016. National total GHG emissions ranged from 35,000 gigagram (Gg) CO_2 equivalent (CO_2-eq) in 1990 to 13,000 Gg CO_2-eq in 2016, reflecting the evolution of the society and its economy (Fig. 1).

After the collapse of the Soviet Union, the economy of Tajikistan suffered significant structural changes that are reflected in the country's GHG emission profile. The share of the energy sector decreased substantially due to the abrupt reduction of fuel consumption in the industry, transport, and residential sectors, but remained the largest sector in terms of GHG emissions in the national inventory of Tajikistan in the period from 1990 to 2016. In contrast to the decreasing contribution of the energy sector to national total GHG emissions, the Agriculture, Forestry, and Other Land Use (AFOLU) sector increased its share in the national GHG emission profile, while the Industrial Processes and Product Use (IPPU) and the waste sectors have been relatively steady in terms of their share during the 1990–2016 period (UNFCCC 2021d; López et al. 2020).

3 Methods

Following approaches used by Fujino et al. (2008) and Naegler et al. (2021) and considerations highlighted in Holmberg and Robert (2011) and Gopinathan et al. (2019), a five-step back-casting approach is developed to assess alternative mitigation pathways for Tajikistan in order to achieve carbon neutrality by 2050 (Fig. 2). The Paris Agreement requires substantial changes in order to reduce GHG emissions in an effort to fulfil its aim to limit global warming to well below 2 °C above pre-industrial levels (1850–1900), while pursuing the means to limit the increase to 1.5 °C. A back-casting approach is considered more suitable as it builds on the concept where future conditions are envisioned and the required steps to attain these conditions subsequently analysed and defined, which supports

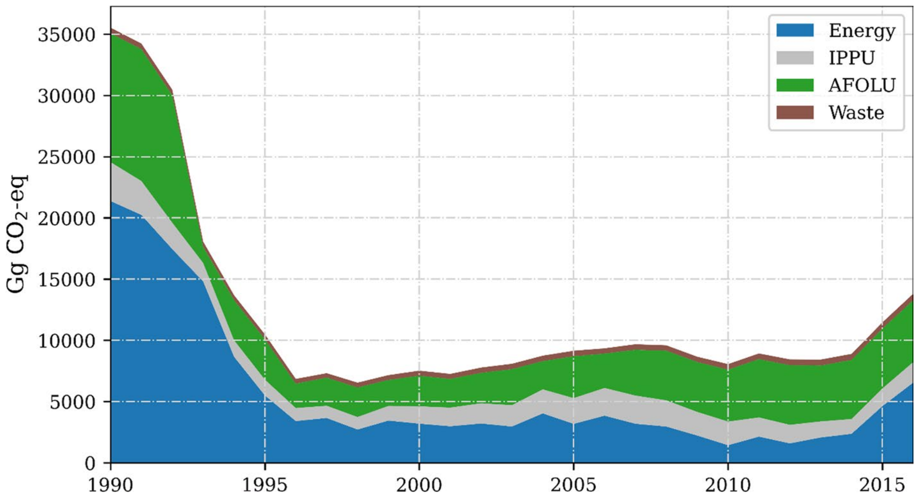

Fig. 1 Historic GHG emission profile of Tajikistan

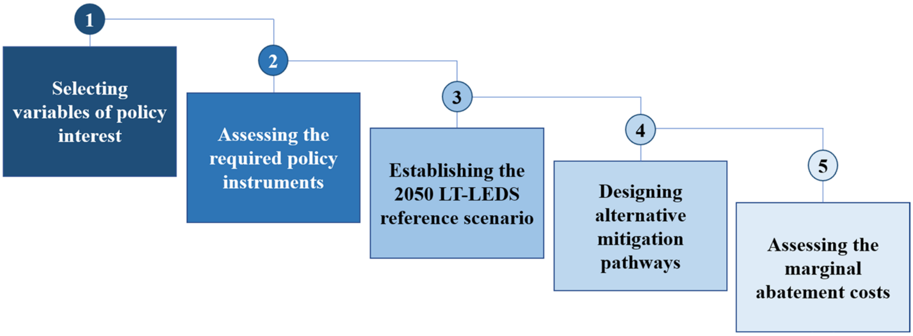

Fig. 2 Illustrative structure of the five-step back-casting approach

countries to move away from unsustainable mitigation pathways that extrapolate current practices into the future (Holmberg and Robert 2011). This approach is designed considering Tajikistan's early exploratory phase, and assesses the requirements that must be met to successfully achieve a future scenario, namely net-zero emissions by 2050.

3.1 Selecting variables of policy interest

Back-casting approaches are framed around a set of guiding principles of sustainability (Holmberg and Robert 2011). These principles can be considered variables of policy interest, which are areas in which climate mitigation policies, actions, or programmes of incentives can be designed and implemented. The intensity of these variables will ultimately define the different mitigation pathways and the policy implications.

All national and sectoral policy frameworks and principle strategic documents in Tajikistan are considered to establish the main objective lines and vision that the country will follow and identify the variables of policy interest for the mitigation pathways (Table 1).

3.2 Assessing the required policy instruments

Long-term strategies require the identification of policy instruments related to the selected variables of policy interest. These instruments will need differentiated efforts and demands according to the selected mitigation pathway. Although the specifications and scope differ for each policy instrument, their main characteristic is to bring about societal change, regardless of intentions, targets or goals, and legal status. Regarding LT-LEDS development, this would relate to reducing GHG emissions in the long term, and policy instruments thus support and play an integral part in the main design of the strategy (Huppes et al. 2017).

Therefore, for each of the identified variables of policy interest, policy instruments relevant to the national circumstances are selected that could be implemented in Tajikistan, further supporting the development of a LT-LEDS in the country (Table 1). The resources used to define each of the policy instruments are based on empirical research on international experiences, with a focus on research conducted in the Central Asia region. Furthermore, the mapping links the policy instruments with the related IPCC categories to facilitate the identification of policy instruments associated to the specific GHG emissions that each policy area affects.

Table 1 Policy matrix for types of policy instruments related to the selected variables of policy interest

Sector	Related IPCC categories	Variable of policy interest	Policy instruments	Empirical research
Manufacturing industry	1A2 manufacturing industries and construction, 2A mineral industry, 2B chemical industry, 2C metal industry	Industrial innovative technologies	Uptake of best-available techniques, minimum energy performance standards, incentives for installation of high-efficient technologies	OECD (2020); IEA (2015); Nilsson et al. (2021)
		Fuel efficiency in industrial sector	Fuel efficiency management programmes, taxes for the internalisation of environmental costs for fuels	IEA (2015); Nilsson et al. (2021)
Transport	1A3 transport, 1A4c agriculture, forestry, fishing, fish farms	Transport efficiency	Mandatory vehicle efficiency standards, tax incentives for fuel-efficient vehicles, and labelling requirements, diesel tax, efficiency requirements for non-engine components	IEA (2015); Cerruti and Huse (2021); Tsoi et al. (2021); Thaller et al. (2021)
		Low-emission transport infrastructure	Improved energy efficient and environmentally friendly transport modes, promotion and improvement of trolleybus network, urban and commercial development policies	IEA (2015); Thaller et al. (2021); UNDP (2021)
		Electric vehicles	Incentives for purchase of electric vehicle, increased taxes on conventional fuels, incentives for electric vehicles' equipment and usage, integrated planning for electric mobility	IEA (2015); Tsoi et al. (2021); Thaller et al. (2021); IRENA et al. (2018)
		Transport fleet renovation	Fleet renewable mandates, vehicle replacement scheme, incentives for retrofitting of vehicles	Cerruti and Huse (2021); Tsoi et al. (2021); Thaller et al. (2021); IRENA et al. (2018)

Table 1 (continued)

Sector	Related IPCC categories	Variable of policy interest	Policy instruments	Empirical research
Buildings	1A4a commercial, institutional, 1A4b residential	Energy efficient buildings	Mandatory building energy codes and minimum energy performance standards, mandatory energy efficiency requirements for building components and equipment, incentives for energy efficient technologies, mandatory audits and energy use reports, building energy labels or certificates, construction products and equipment energy labels or certificates, national targets for market share of net-zero building	IEA (2015); UNDP (2010); Zhang et al. (2021)
Energy industries	1A1 energy industries, 1B fugitive emissions from fuels	Fossil fuel efficiency	Strengthen carbon pricing and phase out fossil fuel subsidies, carbon tax, disclosure policy	Nilsson et al. (2021); IEA (2018)
		Renewable energy	Feed-in tariffs or feed-in premiums, quotas and tradable green certificate scheme, renewable portfolio standards, reduced tax rates for equipment or revenues from renewable energy sales, tax rebates and loan guarantees for renewable energy projects	IEA (2015); Wall et al. (2019)
		Reduction of energy losses	Voltage management policy, demand side management policy	Strbac et al. (2018); NACAA (2015)

Table 1 (continued)

Sector	Related IPCC categories	Variable of policy interest	Policy instruments	Empirical research
Waste	4A solid waste disposal, 4B biological treatment of solid waste, 4C incineration and open burning of waste, 4D wastewater treatment and discharge	Environmental waste management	Policy guidelines for data collection and archiving, limits and restrictions on landfilling, national targets for collection, reuse, and recycling, incentives for innovation, recycling and separate collection, incentives for public participation	Tojo et al. (2006)
		Environmental wastewater practices	Adoption of best-available techniques for wastewater treatment, certification system of wastewater treatment plants, national effluent policy guidelines, incentives for reusage of industrial wastewater	Brinkmann et al. (2016); Bahri (2009)
Agriculture	3A livestock	Sustainable agriculture practices	Integrated pest management practices, weed management policy, incentives for investment in sustainable technologies, subsidies for best management practices, sustainable nutrient management, labelling requirements for cultivated rice	EC (2021); ADB (2009); Smith et al. (2014); Larson et al. (2012); Bachmann (2012)
		Sustainable livestock management	Pasture management policy, subsidies for biotechnological innovation and sustainable technologies, livestock breeding and feeding policy, meat tax, subsidies for sustainable manure management, incentives for research and development efforts	Teague et al. (2011); Lopes et al. (2021); FAO (2019); Sedik (2009)

Table 1 (continued)

Sector	Related IPCC categories	Variable of policy interest	Policy instruments	Empirical research
Forestry and land use	3B land, 3C aggregate sources and non-CO_2 emissions sources on land	Forest conservation and management	Protected areas and set asides for conservation, sustainable harvest policy, incentives for alternative fuels, illegal logging penalties, forest fire management policy	Smith et al. (2014); Börner et al. (2018); FAO (2010)
		Afforestation and reforestation	Yearly afforestation and reforestation targets, facilitation of plantation and restoration efforts, afforestation and reforestation incentives	FAO (2010)
		Integrated land use planning	Integrated production systems, soil conservation programme, research and development on land use planning	Lopes et al. (2021); Chará et al. (2019)
Carbon capture and storage	1C carbon dioxide transport and storage	Carbon capture and storage technologies	Construction grants and production subsidies, investment and production tax credits, ccs mandate	IEA (2012); Finon (2012)

3.3 Establishing the 2050 LT-LEDS reference scenario

The LT-LEDS reference scenario up to 2050 is estimated from the GHG emissions projections of Tajikistan's unconditional NDC scenario (UNFCCC 2021d), which considers the impact of implementing existing and planned policies and measures up to 2030 that do not require attracting additional substantial international funding (López et al. 2020), similar to Sebos et al. (2020). The unconditional NDC scenario incorporates a forecasted macro-economic framework for the country, based on an intermediate evolution of the gross domestic product (GDP) (5.9%), population (2%), and electricity demand (7.4%), according to the National Development Strategy up to 2030 of Tajikistan (Government of Tajikistan 2016).

Macro-economic proxies based on the Government of Tajikistan (2016) are used to project the NDC reference scenario from 2030 onwards to achieve a 2050 LT-LEDS reference scenario using linear models by sector, similarly to Yang and O'Connell (2020) and Lai and Dzombak (2020). The 2050 LT-LEDS reference scenario is modelled considering a maximum increase of nature-based carbon removals by 2050 of + 15% (taking into account that the maximum level of forest cover in Tajikistan in the nineteenth century pre-industrial period was 25% (UNECE and FAO 2019)), a moderate evolution of the GDP (4.1%), and also not considering any additional policy efforts during this time. In other words, it does not take into account the implementation of any additional policy efforts during 2020–2050 but is projected considering different proxies related to the country which drive the sectoral evolution of the inventory (González-Sánchez and Martín-Ortega 2020).

These 2030 NDC and 2050 LT-LEDS reference scenarios (Table 2) will allow the assessment of the unit emission reduction of policy efforts, which relates to the mitigation potential or the potential total national GHG emission reductions that could be achieved in each of the variables of policy interest from the 2030 reference year until 2050.

3.4 Designing alternative mitigation pathways

The set of variables of policy interest are used to define the mitigation pathways for Tajikistan to potentially reach carbon neutrality in 2050, each considering and combining different levels of intensity (Table 3). For instance, a very high intensity of the policy variable will imply the implementation of numerous policies around it, resulting in more GHG emission reduction, but potentially involving higher costs. More ambitious pathways might therefore be less attractive due to the increased financial requirements. These intensities will thus define the mitigation pathways, providing several policy opportunities depending on the country's efforts.

This study applies successive levels of policy intensity (from 0 to 4) involving progressive GHG emission reductions applied to the GHG emissions estimated in the unconditional 2030 NDC and 2050 LT-LEDS reference scenarios, in the IPCC categories associated to the affected policy areas (Freake 2021; Climact 2021). The GHG emission reduction associated to the intensity levels in each policy area is defined considering (i) the theoretical maximum GHG emission reduction by IPCC category; (ii) the potential impact of each policy area determined from a selection of studies (IPCC 2018; IPCC 2014a; EEA 2021); and (iii) the estimated GHG emissions in the 2030 NDC and 2050 LT-LEDS reference scenarios.

Although the outcome of the mitigation pathways is known, namely carbon neutrality, theoretical maximum GHG emission reductions by IPCC category are set as 100 to 70% of 2050 reference scenario emissions, reflecting the lowest level of emissions that

Table 2 National GHG emissions in the latest 2016 national GHG emission inventory, and the 2030 (NDC) and 2050 LT-LEDS reference scenarios (Gg CO_2-eq)

Sector	IPCC category	2016	2030	2050
Energy	1A1 energy industries	2714	6353	7751
	1A2 manufacturing industries and construction	1968	3896	4754
	1A3 transport	1374	2765	3374
	1A4 commercial/residential/institutional	425	792	967
	1B1 fugitive emissions from solid fuels	33	60	73
	1B2 fugitive emissions from oil and natural gas	38	45	54
Industrial processes and product use	2A mineral industry	1032	2020	2464
	2C metal industry	652	1411	1722
	2F product uses as substitutes for ODS	0	0	0
Agriculture, forestry and other land use	3A1 enteric fermentation	4173	4125	5033
	3A2 manure management	1478	1429	1744
	3B land	−1598	−2732	−3142
	3C aggregate sources and non-CO_2 emissions sources on land	1004	1102	1102
Waste	4A solid waste disposal	306	360	440
	4C incineration and open burning	0	0	0
	4D wastewater treatment and discharge	212	247	301
	Total	13,809	21,872	26,637

Table 3 Policy intensity levels considered in Tajikistan's mitigation pathways

Intensity level	Description
0	No intensity—there are no policy efforts undertaken by the country for the sector
1	Limited intensity—some small policy efforts are being made in the sector; however, they do not lead to any significant changes
2	Moderate intensity—additional policy efforts are being made in the sector, but they are not very ambitious
3	Considerable intensity—additional policy efforts are being made in the sector which do lead to significant changes in activities
4	High intensity—thorough policy efforts are initiated in the sector to ensure extensive and sizable changes

could be reached by IPCC category. The GHG emission reductions of the study commence in 2025 considering that mitigation policies require some time to provide emission reduction after their starting date of implementation.

Four mitigation pathways are defined for Tajikistan, each incorporating different intensity levels for the variables of policy interest. The four mitigation pathways are summarised and substantiated as follows:

- Pathway 1—*full decarbonisation of the energy sector*. Although Tajikistan has abundant water resources, and 95% of the installed electricity generation capacity in Tajikistan is covered by hydropower plants, the country is still largely dependent on fossil fuels for its energy power generation, partly in order to improve its energy security due to the seasonality of hydropower (IHA 2019). The National Development Strategy of Tajikistan for the period until 2030 calls for an increase in coal production to 15 million tonnes (Mt) per year by 2040 (Government of Tajikistan 2016). In line with this national vision, Tajikistan has been actively adding coal-fired generation and has reserves of 120 Mt of oil and 880 Mt of gas (Government of Tajikistan 2021). Considering that the energy sector contributed 47.4% to the national total GHG emissions in 2016 and is still the largest sector in terms of GHG emissions in the national inventory (UNFCCC 2021d; López et al. 2020), this heavy dependence on fossil fuels will increase Tajikistan's GHG emissions in the long term. Therefore, the first scenario focusses on decarbonising the energy sector, both in the supply and demand sectors, to assess the feasibility for Tajikistan to reach net-zero emissions by targeting policy actions in the energy sector.

- Pathway 2—*focus on the enhancement of nature-based carbon removals*. The total area of agricultural land in Tajikistan was approximately 3.7 million hectares in 2018, which is around 25% of Tajikistan's total land (Government of Tajikistan 2015), with around 60% of the population dependent on crop or livestock production for their primary source of income, employment, and livelihood (Government of Tajikistan 2019). In addition, the AFOLU sector increased its share in the national GHG emission profile, representing 36.6% of national total GHG emissions in the country in 2016, second after the energy sector (UNFCCC 2021d; López et al. 2020). These aspects highlight the size and importance of the agricultural sector in Tajikistan, and the potential to reduce GHG emissions. Furthermore, the percentage of forest cover in the country is only 2.96% of the total land cover (FAO 2020) and is considerably lower than the approximately 25% of forest cover in the nineteenth century (UNECE and FAO 2019). Considering the large share of GHG emissions from the AFOLU sector, and the opportunities for nature-based CDR, the second scenario focusses on enhancing removals from the forestry and land use sector and in improving the sustainability and decarbonisation of the agriculture sector.
- Pathway 3—*target full decarbonisation of the energy sector and the enhancement of nature-based carbon removals*. The third scenario focusses on both decarbonising the energy sector, enhancing removals from the forestry and land use sector, and improving the sustainability and decarbonisation of the agriculture sector. It assesses the possible scenario for Tajikistan which considers the incorporation of intensive policy efforts in all sectors of society. This provides an overview of the feasibility in terms of GHG emissions reductions without considering additional established technological CDR technologies or other innovative CDR technologies that will evolve in the future, which is deemed an integral part of countries' LT-LEDS to achieve net-zero emissions by the mid-century (Buylova et al. 2021). It therefore incorporates the main focus points of both the first and second mitigation pathways.
- Pathway 4—*focus on the enhancement of current technological carbon removals and other novel technological CDR technologies that will be available in the future*. The fourth pathway adds CDR technologies, both established and innovative CDR technologies that will evolve in the future, to the second mitigation pathway, to assess the possibilities to complement reasonable sectoral policy efforts with the incorporation of novel technologies, as theorised by IPCC (IPCC 2018). This combination was elected due to the high nature-based CDR policy efforts considered in the second pathway and considering their potentially lower implementation costs compared to actions in the energy and industrial sector, which are more profound in pathways one and three, thus keeping in mind country's generally opting for

financially favourable opportunities. A relatively well-established CDR technique is carbon capture and storage (CCS), which captures and compresses emitted CO_2 from large point sources (usually at large industrial installations), transporting it to a suitable storage location, and injecting it into the ground for long-term isolation from the atmosphere (IPCC 2005). However, CCS is solely feasible at electric power and heat production plants and other large industrial facilities (IPCC 2006). The scope of these emission reductions for Tajikistan is defined by the emissions produced under IPCC categories 1A1 energy industries (100%), 1A2 manufacturing industries and construction (50%), 2A mineral industries (50%), and 2C metal industries (50%) (IPCC 2006). Other novel technological CDR technologies still in the theoretical phase, requiring further research and development, such as the utilisation of atmospheric CO_2 as a feedstock for producing plastic, materials, and chemicals for commercial and industrial use (Warsi et al. 2020), or CDR technologies currently being applied at pre-commercial scale, such as direct air carbon dioxide capture and storage (DACCS) (Gambhir and Tavoni 2019), will therefore also be considered. This will allow Tajikistan to extend the scope of carbon removals to other emitting areas such as applying direct air capturing in buildings through HVAC/DACCS-coupling (Baus and Nehr 2022) or applying carbon absorption units to vehicles to capture emissions from the transport sector (Larkin et al. 2022).

The intensity levels are applied to each variable of policy interest (Table 4) according to the objectives and vision of each pathway previously described.

3.5 Assessing the marginal abatement costs

An analysis is conducted to identify the MAC of each of the selected variables of policy interest to assess the cost-effectiveness of the four mitigation pathways, which will allow Tajikistan to weigh the costs and benefits of the policy decisions and avoid financially unfavourable pathways. The assessment is based on published studies related to the costs for similar interventions in other countries to ultimately define a range of costs.

The obtained price ranges in the desk review are adjusted to current year values according to the inflation rates of the consumer price index (CPI) from the United States Bureau of Labour Statistics (BLS 2021). Furthermore, to obtain final MAC ranges in USD, results from studies in Euros (EUR) are converted to USD according to the European Central Bank's (ECB) exchange rate 1 EUR = 1.194 USD (ECB 2021).

The desk review identified five studies that conducted a review of the MAC of mitigation measures, namely: McKinsey and Company (2009) developed a global GHG abatement cost curve beyond business-as-usual by 2030 based on the technologies of the period in EUR per tCO_2-eq; Kesicki and Ekins (2012) is a study by the World Bank that applied a MAC curve built at the World Bank which computed the amount of GHG saved by each measure in the long run (in $MtCO_2$-eq) and the cost of doing so (in USD/tCO_2-eq); Gillingham and Stock (2018) estimated the static abatement costs by comparing the cost in USD per tonne of CO_2-eq abated by replacing electricity generated by existing coal-fired power plants in the USA with electricity generated by a cleaner alternative providing a bottom-up, or engineering, cost estimate of the power sector, and additionally

Table 4 Policy intensity levels in Tajikistan's mitigation pathways

Sector	Variable of policy interest	Pathway 1	Pathway 2	Pathway 3	Pathway 4
Manufacturing industry	Industrial innovative technologies	4	2	4	2
	Fuel efficiency in industrial sector	4	3	4	3
Transport	Transport efficiency	4	2	4	2
	Low-emission transport infrastructure	4	2	4	2
	Electric vehicles	4	1	4	1
	Transport fleet renovation	4	2	4	2
Buildings	Energy efficient buildings	4	4	4	4
Energy industries	Fossil fuel efficiency	4	3	4	3
	Renewable energy	4	3	4	3
	Reduction of energy losses	4	2	4	2
Waste	Environmental waste management	4	2	4	2
	Environmental wastewater practices	4	3	4	3
Agriculture	Sustainable agriculture practices	1	4	4	4
	Sustainable livestock management	1	4	4	4
Forestry and land use	Forest conservation and management	1	4	4	4
	Afforestation and reforestation	1	4	4	4
	Integrated land use planning	1	4	4	4
Carbon capture and storage	Carbon capture and storage technologies	0	0	0	4

by conducting a review of costs interventions in more than 50 economic articles, providing ranges of estimates related to the implantation of different policies in USD per tonne CO_2-eq; Timilsina et al. (2016) is another study conducted by the World Bank that developed a methodology to estimate a MAC curve in USD/tCO_2-eq for the 2015–2035 period for residential and commercial sector energy efficiency measures, which it applied to the building sectors of Armenia and Georgia; and City of New York (2013) evaluated the potential for achieving deep long-term carbon reductions in New York while considering the economic impacts examining the buildings, power generation, transportation, and solid waste sectors and subsequently analysing carbon reduction measures in each of these sectors and the related costs in 2030 in USD per tonne CO_2-eq.

The MAC of mitigation measures within each of the variables of policy interest were obtained from these five studies and the values were adjusted with the inflation and exchange rates to obtain the cost estimates, resulting in the minimum (lower range), maximum (upper range), and average costs in 2021USD to reduce one Gg of CO_2-eq for each of the variables of policy interest (Table 5).

4 Results and discussion

4.1 Emission characteristics of mitigation pathways

The results indicate that each of the four mitigation pathways provides a significant GHG emission reduction potential compared to the 2050 LT-LEDS reference scenario (Table 6 and Fig. 3). The 2050 LT-LEDS reference scenario would result in 26,637 Gg CO_2-eq by 2050, which is an 21.8% increase in GHG emissions compared to the 2030 NDC scenario and an 92.9% increase in GHG emissions compared to the 2016 GHG inventory (Table 4) and is in sharp contrast to the potential significantly lower emission levels in the developed mitigation pathways.

Despite the substantial policy efforts for the decarbonisation of the energy sector in the first mitigation pathway, Tajikistan will not reach carbon neutrality, and will still emit 5488 Gg CO_2-eq by 2050, which is a 60.3% and 79.4% emission reduction compared to the 2016 national GHG emission inventory and the 2050 LT-LEDS reference scenario, respectively. This is partially explained by the lack of intensive policy efforts in the AFOLU sector, which is the second largest GHG emitting sector in the national inventory of Tajikistan. Therefore, failing to incorporate additional policy efforts in the AFOLU sector will still lead to substantial emissions from that sector. Furthermore, although this pathway focusses on intensive policy efforts in the energy sector, residual emissions will remain in the sector as it is not attainable to remove all emissions.

The second mitigation pathway will result in 8235 Gg CO_2-eq by 2050, which is a 40.4% and 69.1% emission reduction compared to the 2016 national GHG emission inventory and the 2050 LT-LEDS reference scenario, respectively. Therefore, this pathway does also not

Table 5 Marginal abatement costs of variables of policy interest (2021USD/Gg CO_2-eq)

Sector	Variable of policy interest	Lower range	Upper range	Average
Manufacturing industry	Industrial innovative technologies	−45,900	87,770	12,859
	Fuel efficiency in industrial sector	−11,470	1430	−4303
Transport	Transport efficiency	9045	1,743,275	305,698
	Low-emission transport infrastructure	−337,890	417,570	37,350
	Electric vehicles	−191,470	530,360	132,590
	Transport fleet renovation	370,415	370,415	370,415
Buildings	Energy efficient buildings	−810,940	372,890	−106,442
Energy industries	Fossil fuel efficiency	1430	11,850	6640
	Renewable energy	−2870	1,749,580	282,469
	Reduction of energy losses	1430	11,850	6640
Waste	Environmental waste management	−146,420	67,580	−31,049
	Environmental wastewater practices	8660	89,220	48,940
Agriculture	Sustainable agriculture practices	−64,540	62,040	−11,608
	Sustainable livestock management	2870	76,690	46,600
Forestry and land use	Forest conservation and management	7170	37,290	20,080
	Afforestation and reforestation	650	20,080	9993
	Integrated land use planning	7170	61,290	34,230
Carbon capture and storage	Carbon capture and storage technologies	46,320	102,320	73,494

Table 6 National GHG emissions in 2050 in Tajikistan's mitigation pathways (Gg CO_2-eq)

Sector	IPCC category	Pathway 1	Pathway 2	Pathway 3	Pathway 4
Energy	1A1 energy industries	0	2325	0	2325
	1A2 manufacturing industries and construction	475	1664	475	1664
	1A3 transport	169	2699	169	2699
	1A4 commercial/residential/institutional	48	48	48	48
	1B1 fugitive emissions from solid fuels	4	44	4	44
	1B2 fugitive emissions from oil and natural gas	3	33	3	33
	1C carbon capture and storage technologies	0	0	0	−8235
Industrial processes and product use	2A mineral industry	616	1602	616	1602
	2C metal industry	431	1119	431	1119
Agriculture, forestry and other land use	3A1 enteric fermentation	4530	1510	1510	1510
	3A2 manure management	1569	523	523	523
	3B land	−3551	−4084	−4084	−4084
	3C aggregate sources and non-CO_2 emissions sources on land	1047	331	331	331
Waste	4A solid waste disposal	88	286	88	286
	4C incineration and open burning	0	0	0	0
	4D wastewater treatment and discharge	60	135	60	135
	Total	5488	8235	173	0

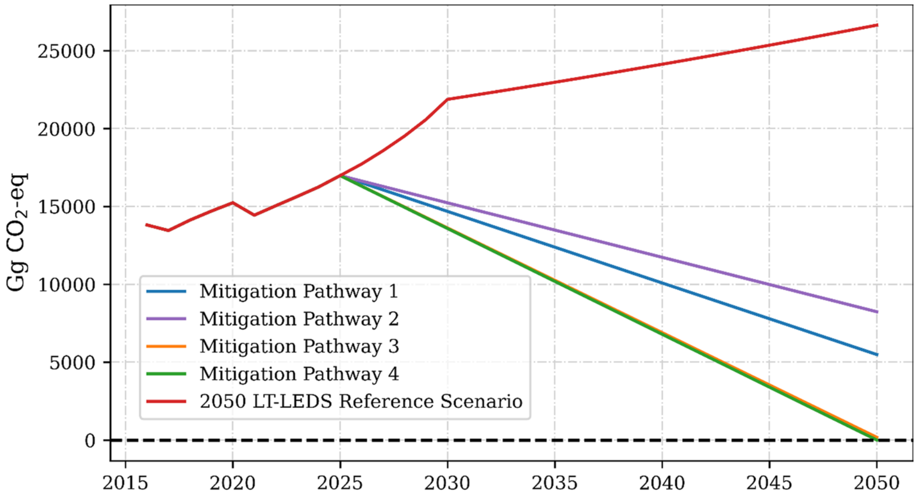

Fig. 3 Illustration of the four mitigation pathways and the 2050 LT-LEDS reference scenario

reach carbon neutrality. This mitigation pathway faces the same issue as the first mitigation pathway, as it focusses on intensive policy efforts related to one main GHG emitting sector, resulting in other sectors still producing large quantities of emissions and therefore hindering the goal of net-zero emissions. These first two mitigation pathways demonstrate that it is not sufficient for Tajikistan to solely focus its policy efforts on one sector emitting large quantities of GHG emissions and requires a more overarching approach that focusses on all sectors of the country.

The national total GHG emissions in 2050 in the third mitigation pathway will be 173 Gg CO_2-eq, which is a 98.7% and 99.4% emission reduction compared to the 2016 national GHG emission inventory and the 2050 LT-LEDS reference scenario, respectively. It reaches considerably lower emission levels than the first and second mitigation pathway, but does not quite reach net-zero emissions, despite the intensive policy efforts in all sectors. This suggests that the incorporation of solely nature-based CDR in the country is not sufficient to reach the goal of carbon neutrality by 2050 and highlights the importance of additional technological CDR activities. Without both established technological CDR technologies and innovative technological CDR technologies which are currently at demonstration level, Tajikistan will be required to pursue GHG reduction rates that are impossible given the timeframe to 2050.

The fourth mitigation pathway will result in 0 Gg CO_2-eq by 2050, therefore reaching carbon neutrality. In addition to policy efforts for nature-based CDR, this is the only pathway that integrates technological CDR activities, both established technologies and innovative CDR technologies that will evolve in the future. The total 8235 Gg CO_2-eq emissions reduced through technological CDR include 4518 Gg CO_2-eq emission reduction through established CCS technologies (1A1 energy industries (100%), 1A2 manufacturing industries and construction (50%), 2A mineral industries (50%), and 2C metal industries (50%)) and 3717 Gg CO_2-eq additional emission reductions which could not be achieved considering the characteristics of the current CDR technologies. These additional emission reductions are thus associated with novel technological CDR technologies, which are still in the theoretical phase or being applied at pre-commercial scale. These technologies are to be applied in different end use sectors, notably in 1A3 transport, but also the further enhancement of emission reductions in 1A2, 2A, and 2C. The fourth pathway highlights the necessity for significant technological progress to be achieved for Tajikistan to feasibly achieve net-zero emissions by 2050, in case very intensive policy efforts are not implemented in all policy areas.

Although this work highlights the need for technological CDR activities to reach carbon neutrality by 2050, the potential barriers and challenges associated with CDR implementation and scale up should be acknowledged. In addition, there are ethical and sustainability considerations linked to the deployment of CDR (Workman et al. 2019), as large-scale nature-based CDR has substantial consequences on land use. This could potentially be an obstacle for Tajikistan to adopt CDR technologies and reach their desired LT-LEDS ambition. It is therefore essential for the country to obtain a better understanding of specific technologies for removals that can be deployed in the country.

Furthermore, the quantitative analysis applied in the mitigation pathways concerning potential emission reduction does not consider the societal implications in the country or the potential technological innovations and change, which can influence the pace at which emissions are mitigated and which are important aspects for Tajikistan to consider while developing their national LT-LEDS. The societal implications of investing in mitigation actions have been assessed by several studies. For instance, Stamopoulos et al. (2021) presented the potential economic benefits that can be achieved through investing in renewable energy technologies in Greece and quantified its effects on a series of socio-economic indicators, including GDP, employment, wages, government income (through taxes), and capital formation (Stamopoulos et al. 2021). The focus on policy efforts also does not directly recognise the political challenges to build domestic capacity required to implement mitigation measures associated with a specific policy. This could be included through an assessment of governance pathways to analyse the political, administrative, and legal requirements for the climate policies to succeed (Gopinathan et al. 2019).

4.2 Cost patterns of mitigation pathways

The assessment of the financial requirements of the four mitigation pathways resulted in the average cost in million 2021USD (Table 7).

The costs for the realisation of the third mitigation pathway are the highest of the four pathways as it incorporates the intensive policy efforts of the first and the second mitigation pathways. This includes policy efforts in decarbonising the energy sector that require large amounts of investment for their implementation such as industrial innovation and energy efficiency, which is also the reason for the first mitigation pathway to be the subsequent most expensive pathway to achieve. The costs of the fourth mitigation pathway are generally high as well, as it includes the introduction of technological CDR activities, while additionally incorporating moderate and intensive policy intensity levels in other areas.

Table 7 Average costs of Tajikistan's mitigation pathways (million 2021USD)

Sector	Variable of policy interest	Pathway 1	Pathway 2	Pathway 3	Pathway 4
Manufacturing industry	Industrial innovative technologies	556.00	288.99	556.00	288.99
	Fuel efficiency in industrial sector	−247.64	−184.22	−247.64	−184.22
Transport	Transport efficiency	9233.10	2595.80	9233.10	2595.80
	Low-emission transport infrastructure				
	Electric vehicles				
	Transport fleet renovation				
Buildings	Energy efficient buildings	−1335.86	−1335.86	−1335.86	−1335.86
Energy industries	Fossil fuel efficiency	27,704.75	20,364.71	27,704.75	20,364.71
	Renewable energy				
	Reduction of energy losses	10.31	4.55	10.31	4.55
Waste	Environmental waste management	−136.60	−60.41	−136.60	−60.41
	Environmental wastewater practices	148.14	102.50	148.14	102.50
Agriculture	Sustainable agriculture practices	−10.13	−113.26	−113.26	−113.26
	Sustainable livestock management	333.16	2682.69	2682.69	2682.69
Forestry and land use	Forest conservation and management	125.60	267.18	267.18	267.18
	Afforestation and reforestation				
	Integrated land use planning				
Carbon capture and storage	Carbon capture and storage technologies	0	0	0	7868.18
	Total	36,380.83	24,612.65	38,768.82	32,480.83

Finally, the second mitigation pathway is the most cost inexpensive to realise. It focusses on policy areas which require less investment or implementation cost for their realisation, such as the forestry and land use sector (Kesicki and Ekins 2012; Timilsina et al. 2016; McKinsey & Company 2009; Gillingham and Stock 2018; City of New York 2013).

The qualitative analysis of the MAC of variables of policy interest applied in this work considered several studies conducted in other countries around the globe. Although these costs might not be directly linked to the country, they do indicate the general economical differences between sectors and technologies, and provide an initial assessment for Tajikistan to indicate the financially unfavourable characteristics of certain mitigation pathways. However, studies emphasise that it is important that a region- or country-specific MAC curve is developed, as they come in a variety of shapes that differ according to national circumstances (Wächter 2013). It is therefore important for Tajikistan to develop a country-specific MAC assessment which considers the characteristics of the nation.

Furthermore, there has also been considerable criticism regarding the application and limitation of MAC curves, as they are often insufficiently transparent about underlying assumptions, lack uncertainty considerations, and fail to address the interaction between strategies (Dunant et al. 2019). This drawback is addressed by integrating the results from different studies and by considering ranges representing the variability of the provided values. However, it remains essential for policy makers in Tajikistan to consider these aspects when interpreting the results of this qualitative analysis and when developing a country-specific MAC assessment.

It should be noted that these four mitigation pathways were selected and elaborated as they integrate the largest emitting sectors, economic circumstances, and ambitions of the country; however, the country is not limited to these possibilities, and there are numerous pathways Tajikistan could follow.

5 Conclusions and future work

This work presents an initial assessment and mapping of alternative long-term mitigation pathways for Tajikistan to achieve carbon neutrality by 2050, providing the country with a starting point to define the considered GHG emissions, desired targets, required policies, and subsequent financial pathways relevant to the national priorities and country goals.

The research indicates that each of the four considered mitigation pathways presents a significant potential GHG emission decrease compared to the 2050 LT-LEDS reference scenario. The first mitigation pathway, which focusses on decarbonising the energy sector, results in a 79.4% emission reduction by 2050 compared to the 2050 LT-LEDS reference scenario. The second pathway targets the enhancement of nature-based removals and improving the sustainability and decarbonisation of the agriculture sector, and the third mitigation pathway focusses on intensive policy efforts in all sectors of society without considering additional technological CDR technologies, and they result in a 69.1% and 99.4% emission reduction by 2050 compared to the 2050 LT-LEDS reference scenario, respectively.

These three mitigation pathways show that Tajikistan will require intensive policy efforts in all mitigation policy areas to be close to achieve carbon neutrality by 2050. It also shows that a combination of intermediate policy efforts in different policy areas allows to achieve relatively low emission levels by 2050 under an expansive macro-economic framework. This calls into question whether the potential negative impacts to the national economy of a very high level of policy implementation outweigh the benefits of achieving carbon neutrality from a very low level of emissions. It also demonstrates the possibility for implementing synergistic policy actions in several areas to achieve ambitious emission reductions while minimising the negative effects on the national economy.

The fourth mitigation pathway, which considers the implementation of CDR technologies over a moderate-high policy scenario, shows that CDR technologies can complement national policy efforts by achieving additional GHG emission reductions while permitting the economy to grow in certain carbon-intensive industries. It also shows that current CDR technologies are not sufficient for achieving carbon neutrality without implementing profound policy interventions in all areas. Remarkable technological progress would be required for Tajikistan to achieve net-zero emissions by 2050, in case intensive policy efforts are not implemented in all policy areas.

The work additionally provides an assessment of the financial requirements of the four mitigation pathways, which was obtained by identifying the MAC of each of the selected variables of policy interest. This shows that energy efficiency interventions in the industry, transport, and residential sectors have the lowest MAC of all considered policies, along the interventions related to sustainable agriculture, forestry, and land use interventions. MAC characteristics made the second mitigation pathway, focused on the enhancement of nature-based removals, the more efficient in terms of costs. Conversely, mitigation pathways one and three involve more expensive interventions which included policies related to infrastructure development. The inclusion of CDR technologies in mitigation pathway four resulted in about 8000 million 2021 USD of additional cost, for an emission reduction of 8235 Gg CO_2-eq.

It is therefore essential for countries to assess the costs associated with any given total amount of GHG reduction to identify the most financially favourable pathways responsible for the reduction of emissions and the avoidance of costs in the long term. This is especially important for developing countries who are already facing larger economic losses from climate-related disasters, and who have fewer financial resources available to address this issue. MAC assessments can facilitate this by combining policy intensities in different sectors to select the most financially favourable approach in combination with emission reductions.

In future work, Tajikistan can build on this initial mapping and development stage, and determine its specific scope and targets to develop a national LT-LEDS. This should include a country-specific MAC assessment which better reflects the national circumstances and will identify the most financially favourable GHG mitigation pathways. The timeframe of the development of a LT-LEDS is very favourable as Tajikistan has recently submitted its updated NDC to the UNFCCC. This will allow Tajikistan to provide a long-term horizon to the NDC, place the NDC into context of Tajikistan's long-term planning and development priorities, and present a vision and direction for future development to ensure the country achieves carbon neutrality.

Furthermore, building from the case study of Tajikistan, this research provides a novel methodological approach aimed at feeding the formulation of LT-LEDS. The consistency with the NDC and the national GHG emission inventory are major strengths of the approach with a significant potential to ease climate change policy making in developing countries.

Acknowledgements The research is based on the technical reports elaborated by the authors funded by the United Nations Development Programme (UNDP) and Foreign, Commonwealth & Development Office (FCDO) to develop Mitigation Pathways for Tajikistan to achieve carbon neutrality by 2050 and to develop the GHG forecasting in key sectors and impact assessment of climate change mitigation policies and measures.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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