World Health Organization

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Abbreviations and acronyms

AFOLU	agriculture, forestry and other land use
AIM/CGE	Asia-Pacific integrated assessment/computable general equilibrium
ARE	alternative and renewable energy
AVERT	avoided emissions and generation tool
BAU	business as usual
BC	black carbon
BCR	benefit-to-cost ratio
BenMAP	Environmental Benefits Mapping and Analysis Program
CBA	cost–benefit analysis
CEA	cost–effectiveness analysis
CGE	computable general equilibrium
CIS	climate information services
CLD	causal loop diagram
CMAQ	community multiscale air quality
CPI	comprehensive pollution index
CRA	comparative risk assessment
IER	integrated exposure response
CSA	climate-smart agriculture
DALY	disability-adjusted life year
DEM	digital elevation model
DMC	Directorate of Malaria Control of Pakistan
EASIUR	estimating air pollution social impacts using regression
EPA	Environmental Protection Agency
EPSTEIN 2.0	environmental policy simulation tool for electrical grid interventions v2.0
ETS	emissions trading scheme
EWS	early warning system
FGPH	Federal Government Polyclinic Hospital
GCM	global climate model

GDP	gross domestic product
GEM	green economy model
GEMM	global exposure mortality model
GHG	greenhouse gas
GIS	geographical information system
GSI-IF	global subsidy initiative – integrated fiscal model
GST	general sales tax
HAB	harmful algal bloom
HEC–HMS	Hydrologic Engineering Center–hydrologic modelling system
HLY	healthy life year
HNAP	health national adaptation plan
HPI	heavy metal pollution index
IAM	integrated assessment model
IIASA	International Institute for Applied Systems Analysis
IISD	International Institute for Sustainable Development
IMED	integrated model of energy, environment and economy for sustainable development
InVEST	integrated valuation of ecosystem services and tradeoffs
IPCC	Intergovernmental Panel on Climate Change
IPPU	industrial processes and product use
IRR	internal rate of return
LPG	liquefied petroleum gas
LNG	liquefied natural gas
LULC	land use and land cover
LULUCF	land use, land-use change and forestry
MCA	multi-criteria analysis
MEPS	minimum energy performance standards
NAP	national adaptation plan
NBI	nature-based infrastructure
NDC	nationally determined contribution
NEECA	National Energy Efficiency and Conservation Authority
NEMO	network emission model
NPV	net present value

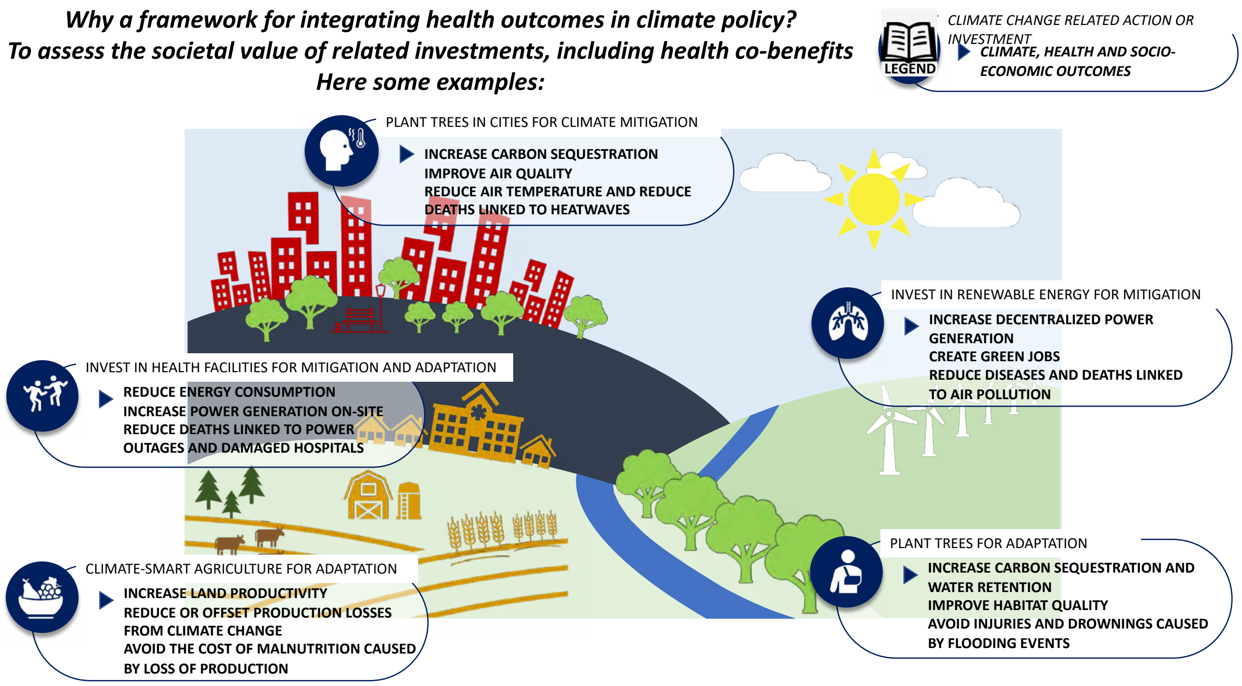
ÖNACE	Austrian statistical classification of economic activity
PAM	policy assessment model
PEC	Pakistan Engineering Council
PM	particulate matter
QALY	quality-adjusted life year
RAI	risk assessment index
RCM	regional climate model
RCP	representative concentration pathway
RPS	renewable portfolio standards
SAVi	sustainable asset valuation
SCC	social cost of carbon
SDGs	Sustainable Development Goals
SOC	soil organic carbon
Solar PV	solar photovoltaic
SRI	system of rice intensification
SSP	shared socioeconomic pathway
ST	systems thinking
SWAT	soil and water assessment tool
UHI	urban heat island
UNFCCC	United Nations Framework Convention on Climate Change
UV	ultraviolet
VOLY	value of a life year
VRE	variable renewable energy
VSL	value of statistical life
VLYL	value of life year lost
WASH	water, sanitation and hygiene
WFP	World Food Programme
WHO	World Health Organization
WtE	waste to energy
WTP	willingness to pay
YLD	years lost due to disability/years lived with disability
YLL	years of life lost

1 Introduction: why a framework to model climate/policy effects on health?

The United Nations Sustainable Development Goals (SDGs) highlight the interconnections between different aspects of socioeconomic development. The SDGs stress that health is heavily interconnected with nutrition, poverty, education, energy and other infrastructure, and economic development *(1)*. At the same time, the decisions we make to stimulate economic development, via investments in energy, agriculture and infrastructure, to cite some examples, have severely impacted the speed and severity of climate change, leading to multiple health effects. As a result, health is at the centre of several dynamics, contributing to socioeconomic development while at the same time being impacted by it. Health should be considered more broadly in policy and development decisions. But this complex landscape makes the tasks of decision-makers challenging, both due to the uncertainty of weather events and their impact on human health, and to the strong interrelations existing between climate, health and socioeconomic as well as environmental performance. Arguably, one of the most challenging tasks is to determine the health costs of climate change and the health co-benefits of climate change mitigation and adaptation interventions, using a systemic approach. While it is important to integrate knowledge from different scientific disciplines to address specific policy questions *(2)*, climate change policy assessments often lack the identification, integration and analysis of health impacts from climate change *(3)*. Integrating health in the assessment of the costs and benefits of climate action can reveal benefits that are normally not considered in sectoral planning, such as in the energy sector *(4)*. Including such indirect benefits can have important policy implications, and possibly determine whether or not an investment in climate mitigation or adaptation is economically viable *(5)* from a broader societal perspective. Forecasting the health cost of inaction and the health co-benefits of climate action allows to reduce pressure on future decision-making, increasing flexibility of subsequent decision-making by making the multidimensional value of current decisions explicit in the context of a changing climate. On the other hand, challenges remain in the identification of specific climate change impacts, as opposed to those caused – or exacerbated by – development paths (i.e. the definition of risk as a result of exposure, vulnerability and adaptive capacity).

Developing a framework to link science, policy and practice for a comprehensive assessment of climate mitigation and adaptation investments and their impact on human health can inform decision-making in several ways. First, it sets the stage for the creation of a systemic assessment that better reflects the complexity of the real world. Second, it allows for knowledge integration, between health economics and policy assessment across sectors. Third, it links policy-making across sectors, highlighting how health is at the centre of development. Fourth, it can result in valuable health gains, including reductions in health care financial costs, as a co-benefit, when implementing climate mitigation and adaptation investments. Figure 1 shows an example of how this framework would work and what aspects are considered.

Fig. 1. Rationale for the creation and use of a framework that integrates health outcomes in climate policy analysis



Building on the above, this report presents a framework developed to address the needs expressed by leading experts and emerging from a comprehensive literature review. The framework proposes to use weather and climate data to forecast health impacts over time *(6)*; it aims to complement this information with the use of biophysical and economic models to quantify the outcomes of investments in climate change adaptation and mitigation for relevant sectoral indicators and health co-benefits *(7)*; it provides guidance on the economic valuation of health co-benefits of climate action, for inclusion in sector-specific cost–benefit analysis (CBA) *(8)* including the spatial allocation of such costs and benefits *(9)*.

The framework developed and presented in this study is comprehensive, and provides various entry points for different audiences. These include decision-makers in the public and private sectors, researchers and scientists, working in the health sector as well as in other thematic areas (and related sectors) affected by climate action, as explained in chapter 2. The framework does not suggest using specific methods and models. Instead, it provides information on how to best identify relevant indicators, select methods and models that can quantify such indicators, interpret the results of the analysis performed in relation to the strengths and weaknesses of the methods chosen, and finally it shed lights on two different but complementary methods available to prioritize intervention: CBA (with emphasis on economic viability) and cost–effectiveness analysis (CEA) (with emphasis on the outcome, and the effort required to realize it). This comprehensive approach is necessary because any policy assessment has to both (i) take into account the complexity of the context analysed and (ii) produce outputs that are relevant to decision-makers in the different sectors of policy domains. Item (i) is important because it determines how the results of a modelling exercise should be interpreted. For instance, does the model exclude any specific driver of change that plays an important role in causing the problem? If it does, the results will have to be interpreted taking into account such shortcoming of the model. Item (ii) is important because it indicates whether the analysis has the potential to inform decision-making, with the desired type of information, both for causes and for effects of policies and investments. Practically, if a health issue emerges due to environmental degradation, a model should include environmental dynamics, consequences for health, as well as an estimation of the cost of action and inaction. A partial analysis that captures only environment or health dynamics may result in an incomplete economic valuation of action and inaction.

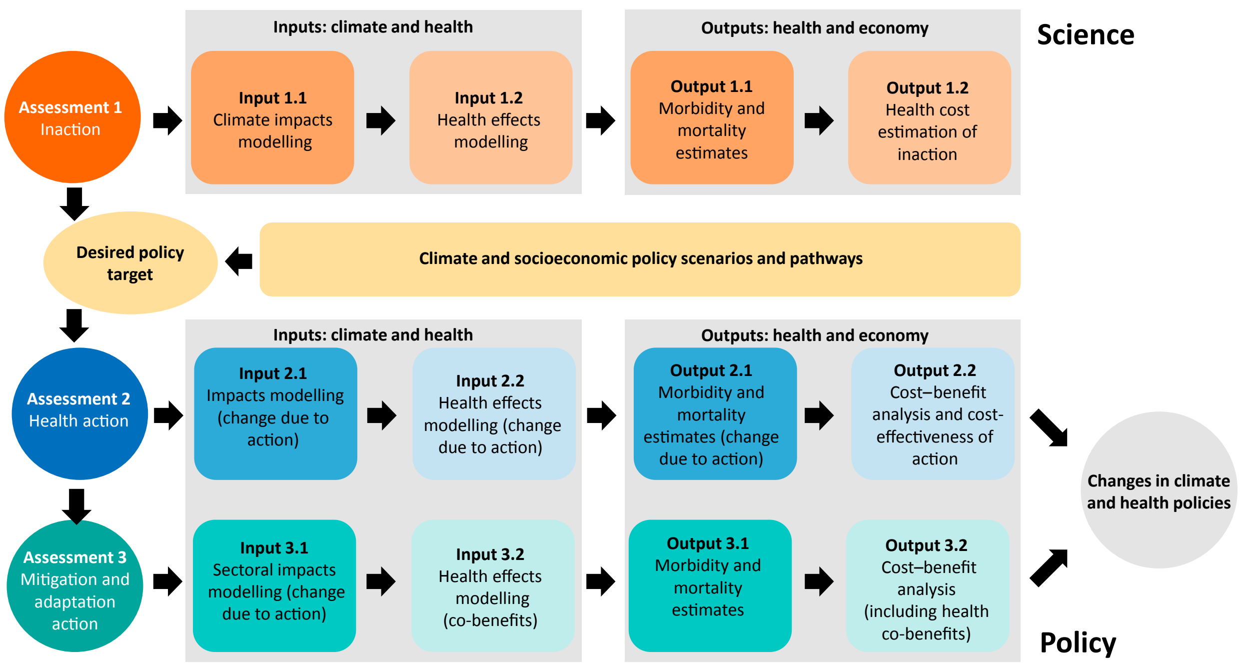
While a broad framework is presented, the goal of this report is not to offer a guide for CBA or CEA of any policy or investment in climate adaptation or mitigation. Instead, the focus of this report is on the economic valuation of health outcomes, either as direct outcomes of health policy or as co-benefits of policies and investments implemented in health- and non-health-determining sectors. Further guidance is offered on the potential use of the economic valuation of health impacts of climate action and inaction for informing policy development, using CBA and CEA.

2 Overview of the conceptual framework and its relevance for quantitative assessments

2.1. Setting the stage for knowledge integration

Figure 2 shows the envisaged sequence of tasks in policy analysis for a comprehensive assessment of climate-related health costs and co-benefits generated by climate action. Each Assessment described in the figure represents a different step that would normally be conducted by a different discipline (scientists, policy-makers in the health, climate adaptation and mitigation domains), providing different entry points for different audiences, and showing the complementarity of their work *(10,11)*.

Fig. 2. Envisaged sequence of tasks in policy analysis for a comprehensive assessment of climate-related health costs and co-benefits generated by climate action



From the top, the starting point is an assessment of the outcomes of a scenario of inaction (Assessment 1), which will be considered as the baseline scenario to trigger policy questions based on the cost of inaction. This includes the consideration of inputs in the review of representative concentration pathways[a] (RCPs) and shared socioeconomic pathways[b] (SSPs) *(13–16)* to develop possible policy, population and technology future trajectories such as "Below 2°C by 2050" *(17)*. Next is the creation of the baseline scenario estimating the outputs, i.e. the health costs of inaction related to climate change. For instance, this may include air pollutant concentration, estimated impact on morbidity and mortality, estimated economic costs *(9,18,19)* considering that there is no adaptation or mitigation policy to address those nor related investment decisions are taken.

This Assessment 1 phase is most likely to be carried out by researchers or scientists. Making use of this information, largely based on the observation of data and the use of simulation models (both for back-casting and forecasting), under a scenario of inaction, the policy ambition can be defined. A desired and feasible policy target is normally identified, e.g. reducing morbidity and mortality from heat stress *(20)* below either a current value or a future estimate.

The policy target provides useful information for the creation of a strategy. As a next step, the perspective of the health sector can be taken, with interventions aimed at improving prevention and treatment (Assessment 2). Impact modelling is carried out first, to then move to health effects and the economic valuation of the outcomes of policy implementation, i.e. health-related policies. For example, for extreme heat, this could include an analysis of the relationships between different temperature levels and specific health outcomes in a particular location, as well as the role of potential confounding factors such as air pollutant levels *(20)*. This work would support the identification of available intervention options, for instance aimed at curbing the impact of expected heat stress. Examples may include investments in air conditioners, or the introduction of climate information services (CIS) and early warning systems (EWS) to warn of the potential severity of future extreme heat events and plan for mitigation actions (e.g. support the logistical effort of distributing water or supporting those in need in their households). It is important to take into account that climate impacts on health, and consequently their costs, will differ depending on the climate pathways and scenarios, and so policy interventions and investments have to be tailored to a specific location and climate scenario.

Next, a similar assessment should be carried out by policy-makers in other sectors, to estimate the health co-benefits of climate action (Assessment 3), using the same health impacts studied in the examples of Assessment 2. This would generate an additional scenario that would estimate, along with the cost and direct benefits of the climate adaptation or mitigation intervention, as well as the resulting health impact and health co-benefits realized *(16)*. For instance, the planting of trees or the use of other forms of green infrastructure may be envisaged to reduce greenhouse gas (GHG) emissions (via carbon sequestration) and air pollution, in a climate mitigation policy exercise. On the other hand, there are additional co-benefits to consider, such as increased water retention (which would reduce the risk of floods in urban areas) and cooling (which would support addressing the issue of heat stress mentioned above) *(21)*. As a result, interventions planned to achieve a given goal, in this case the reduction of GHG emissions and air pollution, may end up contributing positively to other, apparently disconnected, goals (in this case stormwater management and extreme heat).

The outcomes of Assessments 2 and 3 should be then used by decision-makers to assess and prioritize options for interventions (see chapter 4). It is important that the analysis is performed considering different climate and socioeconomic scenarios (e.g. RCPs and SSPs mentioned above), for which outcomes should be compared. For instance, in the case of the previous example, green infrastructure may be a viable option for achieving the GHG mitigation target, but may only curb the impacts of heat stress in a mild global warming scenario (e.g. RCP2.6 and RCP4.5), and would not be sufficient to reach the health-related target in a high warming scenario (e.g. RCP6 and RCP8.5). It seems that, while the intervention

[a] Representative concentration pathways (RCPs) are described in the Fifth Intergovernmental Panel on Climate Change (IPCC) Assessment (2014) *(12)* and widely used in climate modelling. RCPs are four scenarios that outline future trajectories of greenhouse gas (GHG) emissions and their concentrations over time (IPCC, n.d.).

[b] Shared socioeconomic pathways (SSPs) complement and contextualize the RCPs. SSPs are five pathways that outline future scenarios of socioeconomic development in the absence of climate policy (IPCC, n.d.).

chosen can create synergies, the level of ambition for implementation has to be defined based on more than one target, in this case for GHG mitigation and for health outcomes. It is for this reason that the results of the three assessments included Fig. 2 can be used to test the outcomes of different levels of ambition, estimating the costs and health co-benefits of more stringent climate action compared to a baseline scenario[c] *(9,13)*. In setting targets, it is important to also consider costs and benefits by region *(19)*, economic sector *(2)*, and socioeconomic group, highlighting the relevance (or incidence) of health co-benefits making them comparable to other costs and benefits.

Continuing with our example, research framing of adaptation to extreme heat varies among countries: in higher-income countries, research treats heat adaptation primarily as a health issue, whereas in lower-income countries, it often treats heat adaptation as an agriculture- and livelihood-related issue *(21)*. This may reflect earlier findings that the agriculture sector in higher-income countries is much less concerned with climate change adaptation; this also may reflect current research priorities that include heat impacts on urban lifestyles and infrastructure in higher-income countries, in contrast to lower-income countries where heat is often placed in the context of hydrological impacts of climate change in agriculture *(21)*.

Analysing these specifics can help design cost-effective policy packages that balance different co-benefits of action to address extreme heat.

2.2. Elaborating a conceptual framework

The approach presented in Fig. 2 has a series of benefits. First, as indicated above, it links science (Assessment 1) with policy (Assessments 2 and 3). Practically, the assessment of the cost of inaction is expected to stimulate policy intervention, which is then analysed in more detail with a health-specific approach as well as considering the potential contribution of other, possibly already ongoing, policy processes that would result in the creation of co-benefits (e.g. the elaboration and implementation of a transport electrification plan would lead to, among other outcomes, the reduction of air pollution in densely populated areas, especially if electricity would be generated with renewable energy).

Second, it shows the potential to integrate knowledge and results from health economics and from other disciplines, e.g. engineering in relation to infrastructure plans in the context of climate mitigation, or biology and agriculture in the context of climate mitigation. Health economics would contribute and economic valuation of health co-benefits of climate action that can, and should be integrated in sectoral CBA, or project finance assessments.

Third, it indicates that policy action to improve the performance of the health sector can be triggered within the health sector (Assessment 2) and from non-health sectors (Assessment 3). The potential impact of the latter should not be underestimated, given the emphasis that climate mitigation and adaptation have received in the past decade. If the inclusion of health co-benefit in the economic analysis of climate mitigation and adaptation investments makes such investments more attractive and economically viable, then there is a synergy to be realized for the health sector. This being said, it is critical to highlight the role of Assessment 1 (cost of inaction) in raising awareness about current and future health-related challenges that merit policy attention.

Fourth, it highlights two different but complementary methods for prioritizing action: CEA (a comparison of cost and outcome) and CBA (a comparison of cost and the economic value of the outcome). Assessment 1 identifies the areas where intervention is needed to avoid impact, supporting primarily CEA; whereas Assessments 2 and 3 identify areas where investments are economically viable, and primarily support CBA.

Finally, the framework shows that climate change presents opportunities for different sectors to work together *(22)*. Addressing climate change effectively requires that policy planning in the health sector is coordinated with other sectors, with climate change mitigation and adaptation being an example. If this coordination is realized, it will be possible to implement a "health in all policies" approach.

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[c] This would be the outcome of Assessment 1 in Fig. 2.

Figure 3 presents an overview of the conceptual framework that would be applied in the implementation of Assessments 1, 2 and 3 as mentioned above. This framework has three main elements: (i) key drivers of health impacts; (ii) required indicators for a quantitative analysis; and (iii) available methods and models.

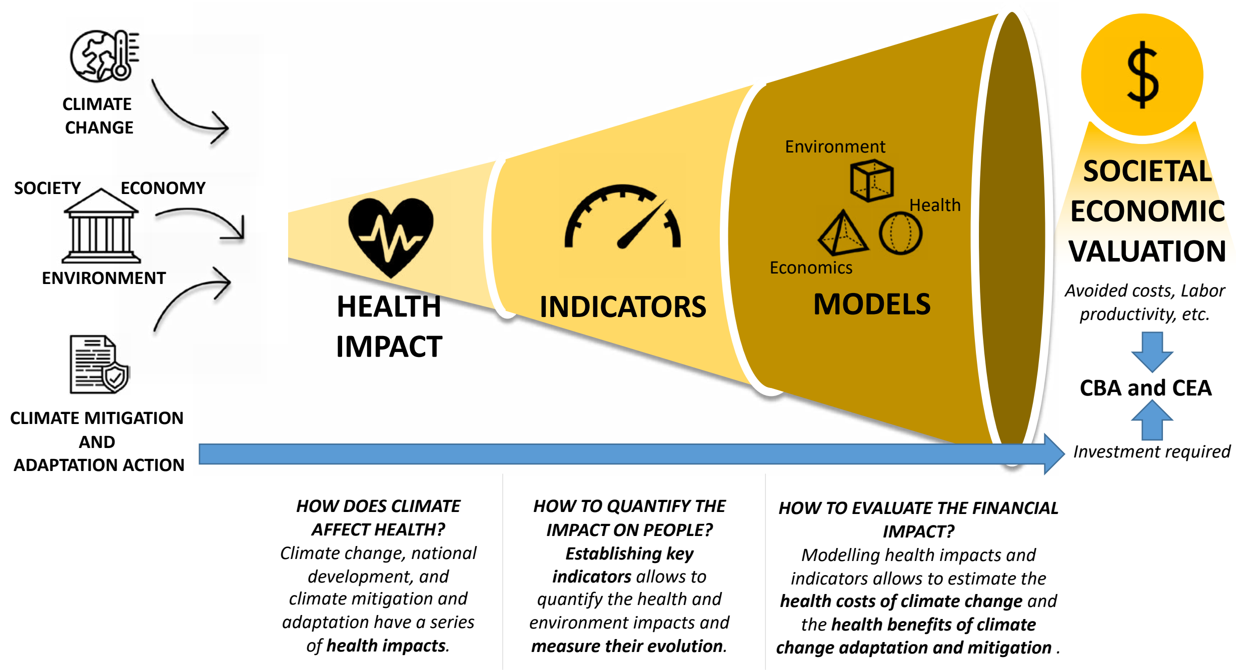
The starting point for the analysis is the policy need. Since every model is built for a purpose, rather than for the analysis of whole systems (i.e. a model is built to represent the system, but it considers that part of the system which is required to explain and analyse concerns and policy/investment impacts), it is crucial to identify "for what reason do we need a model" to define the type of model we need. In this study we consider three main reasons: (i) **policies or investments** may be required to reduce the impact of climate change on health (top left corner); (ii) action may be needed to **reduce the impacts** that current development, society and economic growth strategies are having on air, water pollution and hence on human health (centre left); and (iii) when climate action is being envisaged, **health co-benefits or harm** may emerge (bottom left corner). In this context, we consider both climate mitigation (with the health co-benefits that may emerge from efforts to reduce GHG emissions) and climate adaptation (with direct as well as indirect health benefits, emerging from action in land management, water use and its disposal, and infrastructure – as key benefits).

This framework has been developed using systems thinking (ST). ST is used to simultaneously account for (i) direct, indirect and induced impacts on health, from action and inaction, as well as (ii) the social, economic and environmental drivers that may cause health concerns or offer solutions to health issues. Direct impacts represent a direct consequence of the policy or investment implemented (e.g. transport electrification with the use of renewable energy has a direct impact on liquid fuel use and air emissions – by reducing them). Indirect impacts represent the consequences of the direct impact of policy implementation (e.g. electrification leads to reduced fuel use and air pollution, and hence reduces the number of people suffering from respiratory diseases). Induced impacts take the causal chain even further (e.g. reduced cases of respiratory diseases result in higher labour productivity, income creation and access to health, improving both economic activity and human health). As a result, the framework covers a wide variety of policy outcomes. It seems that, given the central role of health in shaping socioeconomic development and in being affected by it, it will be possible to identify direct, indirect or induced policy or investment outcomes that are connected to health. In this respect, the use of ST allows to explore and make sense of the complexity that gives rise to synergies and unintended consequences, both positive and negative, across social, economic and environmental indicators as well as over time.

Once health impacts are identified, along with the causal paths that determine their emergence, relevant indicators are identified for causes, health consequences, and their effects (see chapters 3.1 to 3.3). These are the indicators that simulation models should include to perform an analysis that is complete (i.e. an analysis that takes into account the complexity of the context analysed) and relevant to decision-makers (see chapter 3.4).

Among available models, we consider those that can quantify and forecast the socioeconomic drivers of change that determine the emergence of health impacts, those that can quantify health impacts, and finally those that can carry out an economic valuation of health impacts, under scenarios of action and inaction (see chapter 3.5). As a result, we do not cover all possible models that can inform decision-making for all dimensions of climate adaptation and mitigation, but only those directly relevant to the estimation of direct health outcomes or health co-benefits. Further, the literature review considers both stand-alone models (i.e. sectoral, thematic models), nested (i.e. sectoral models connected to one another) and integrated models (i.e. sectoral modules integrated in a single model). As a result, the economic valuation can be performed using one or more simulation models.

Fig. 3. Overview of the conceptual framework, resulting in the creation of a systemic cost–benefit analysis (CBA) and cost– effectiveness analysis (CEA)



3 Implementing the framework

This section provides an overview of the main components of the proposed framework, following a step-by-step approach. First, development impacts on health are explored. Second, development trends are assessed, also to identify side-effects for health. Third, intervention options for climate mitigation and adaptation are introduced. Fourth, a broad range of indicators is discussed, for the creation of a systemic assessment of the outcomes of climate action that includes health. Fifth, methods and models for the quantification of such indicators, and the economic valuation of health co-benefits are reviewed.

It is worth considering that the analysis could be further expanded to capture the impact of policies in areas other than climate action, for instance considering social moderating factors, such as impacts of the level of education on health. These are not explicitly considered at this stage, although section 5 provides examples on the extent to which policies implemented to support socioeconomic development can create health co-benefits, in an indirect and induced way. Annex 1 provides a summary of health impacts and their causes, in relation to weather, climate trends and dynamics.

Many of the health impacts considered are interrelated. For instance, action to reduce the consumption of fossil fuels under climate change mitigation policies will also have positive impacts on reducing air pollution, and, in the longer term, should also reduce the effects of climate change in health via climate mitigation. These interconnections will be considered when analysing the methods and models to develop the framework, indicating up to which extent they are considered and potential gaps when establishing the relationships.

This review of the literature is not exhaustive. Its main purpose is to identify what is the breadth of health impacts that should be considered when carrying out policy or investment assessment. The goal is to expand the boundaries of the economic analysis as much as possible, in alignment with the data available.

3.1. Step 1: Identify development impacts on health

The three main health impacts of socioeconomic development analysed in this study are: air pollution (primarily caused by the combustion of fossil fuels and climate dynamics), solid waste (caused by material use, and the lack of proper infrastructure for waste collection, sorting, treatment, recycling and reuse of disposal), and wastewater management (caused by population, and the lack of wastewater management infrastructure for the collection and treatment of wastewater). These areas are chosen as primary impacts of socioeconomic trends on human health, and can be impacted by climate change as well as by climate mitigation and adaptation policy.

3.1.1. Air pollution

The largest single environmental health risk is air pollution (both household and outdoor air pollution), which is responsible for approximately 7 million deaths each year *(23)*. Ambient air pollution is caused primarily by the combustion of fossil fuels for electricity generation and transport *(24,25)* impacting human health in various ways *(26)* (Lelieveld, et al., 2019). Examples of air pollutants include SO_3, NO_2, NO, CH_4, CO_2, CO, methane, and particulate matter, such as black carbon.[d] Ozone is also considered in some estimates *(19,26)*. Air pollution and climate change are closely related. Some pollutants, such as CO_2, ozone and black carbon are also GHGs, affecting the temperature of the planet. Some of the most relevant consequences of air pollution on health include respiratory diseases, cardiovascular damage, fatigue, headaches and anxiety, irritation of the eyes, nose and throat, damage to reproductive organs, nervous system damage *(27)* (Acciona, 2019). (See Annex 1 for more details.)

The harmful impacts of air pollution affect children, women, and people living in poverty in particular *(28)*. For example, during the development stages of infants (including *in utero*) the exposure to air pollutants can result in cardiovascular diseases and cancer later in life, as well as impact cognitive performance *(29,30)*.

An important component of health risk assessment for air pollution is the evaluation of exposure *(31)*. While the measurements of ambient air pollutants are at the core of air pollution epidemiology, the application of such measurements is usually limited by their temporal and spatial coverage. Further, data harmonization is lacking due to the different procedures and methodologies for measuring air pollution and exposure. In this context, remote sensing and global chemical transport, and local land-use regression models, combined with surface monitoring, can increase data availability on key air pollutants. Comparative risk assessment (CRA) can provide comparable estimates for different risk factors linked to mortality from air pollution, but they require consistent methods to be utilized to assess risks *(31)*. Moreover, in the absence of direct epidemiological evidence on mortality risk from exposure to air pollutants, integrated concentration–response functions (integrated exposure response [IER]) can be used for such purposes.

Assessments of morbidity are usually more difficult to conduct than the ones on mortality due to the limited number of air pollution epidemiology studies quantifying the morbidity risks linked to air pollution exposure *(31)*. An approach consists of transferring morbidity rates from areas in which they are available to locations in which they are not and interpolating those rates using methods such as the Bayesian disease mapping and gradient boosted regression trees *(31)*

Air pollution and climate change interact in the creation of health impacts: on the one hand, increasing levels of GHG emissions can lead to temperature changes that can alter the chemical composition of the atmosphere *(32)*; on the other hand, rising temperatures from climate change can increase the concentration of air pollutants such as ground-level ozone, exacerbating air pollution.

3.1.2. Solid waste

Waste generation is a consequence of artificial processes related both to production and consumption, and globally around 8 billion tonnes of waste are produced annually *(33)*. Waste management has important implications for both human health and well-being, in addition to the links with climate change (see section 2.3.2). Scientific evidence suggests the likely occurrence of negative effects including cancer, malformations, mortality, and also less severe but still serious impacts affecting well-being *(23)*. High incidence of cancer and lymphoma has been found in populations living near contaminated sites and landfills (e.g. kidney, larynx, pancreas, liver, lung cancer) as well as higher risks for congenital malformations, low birth weight and neural tube defects. Other health problems concern noise, smell and issues due to annoyance, lowering the quality of life of affected residents *(34)*.

To assess the health risks posed by solid waste, studies generally focus on the assessment of health effects based on proximity to landfills, incinerators, dumpsites, and open burning sites *(33)*. Due to its proximity to people, municipal solid waste can significantly impact human health. Different types of waste can have various and diverse environmental and health impacts depending on the disposal method used (Box 1). For instance, plastic waste is ingested by organisms, causing health impacts through food chains and eventually including also humans. Emissions from waste treatments caused around 3.5% of all global GHG emissions in 2006.

[d] Black carbon, commonly known as soot, is a tiny particle formed by the incomplete burning of fossil fuels, biofuels and biomass (source https://eua-bca.amap.no/background).

Box 1. Examples of health impacts from solid waste management

Kanhai et al. (2021) *(35)* model the health impacts of solid waste management techniques in Accra, Ghana, finding that ceasing open burning of waste would result in a 50% reduction in CO_2 equivalent emissions, and in reduced mortality from PM2.5 emissions, by 2030. In another study from Accra, Boadi et al. (2005) *(36)* suggest that unsafe household solid waste storage and disposure practices are linked to respiratory infections, malaria, diarrhoea and other diseases.

Tait et al. (2020) *(37)* review the health impacts of waste incineration, suggesting that dietary ingestion of pollutants can be a problem for both nearby and distant residents of areas with incineration sites; due to dearth of related studies the observed effects may be underestimated. Similarly, residents living near informal e-waste recycling centres in China are found to be exposed to significantly higher pollutant emissions compared to reference sites, with potential long-time health consequences as pollutants accumulate in water, soil, air and the human body; these impacts are likely to be underestimated *(38)*.

According to Cole-Hunter et al. (2020) *(39)*, waste to energy (WtE) may increase exposure to chemical and pollutant emissions, but the level of those emissions may be lower than those from landfill and traditional incineration. However, there are few related epidemiological studies and robust modelling of the impacts, and the authors specify that the quality of WtE design, management and inputs will likely impact the emission levels.

3.1.3. Wastewater

Wastewater is one of the main sources of environmental pollution since it is usually discharged into water bodies with little or no treatment due to the poor availability of treatment facilities in resource-constrained countries *(40)*. When it comes to the negative consequences of wastewater impacts on human health, existing research mainly focuses on diseases caused by micropollutants (such as heavy metals and fertilizers) and microorganisms (bacteria, protozoa and viruses), which represent the source of many waterborne outbreaks *(41)*. Microorganisms can cause diarrhoea, skin and tissue infections and dysentery, while other disease-causing bacteria such as *E. coli* O157:H7, Salmonella, Vibrio and leptospirosis, can be found in untreated wastewaters (Box 2).

Box 2. Examples of health impacts of wastewater treatment

A review of the literature on wastewater treatment effects on health *(42)* mentions the presence of harmful substances in wastewater, such as polychlorinated biphenyls, in concentrations above allowed limits, which also affects river water. Another study of the health impacts of pollution from distilled wastewater *(43)* concludes that such water contains pollutants with toxic, carcinogenic and mutagenic effects, which can be addressed through integrated treatment processes.

Some areas, particularly in the global South, can be particularly affected. For example, a study of the impact of wastewater and sludge disposal from sewage treatment plants in several Indian cities *(44)* reveals the presence of cadmium, chromium and nickel at higher than allowed levels, resulting in their presence in human blood and urine, indicating a significant health impact in the exposed areas. A study of health impacts of wastewater irrigation in Bolivia, a practice commonly used in agricultural areas experiencing water scarcity *(45)*, finds significant health risks associated with using water from small-scale wastewater treatment plants, including due to weak operation and maintenance practices.

Climate change, together with urbanization and agriculture are the main factors contributing to water pollution, allowing the formation of harmful algal bloom (HAB) events *(46)*. HABs decrease water quality, remove oxygen and pollute water with toxins harmful to both wildlife and humans. Several options are available to decrease the amount of nutrients reaching a water body, one of the main causes of HABs. For example, wastewater treatment facilities and centralized sewage systems can reduce the number of harmful pollutants reaching water bodies.

To quantify and forecast the health impacts of wastewater on water quality, indices that estimate water contamination are required *(47)*. Examples include the heavy metal pollution index (HPI), comprehensive pollution index (CPI), and the imbalance of nutrients in a water body, possibly resulting in HAB and hypoxic events. Besides, the probability of health risks that may be linked to drinking polluted water can be classified using the risk assessment index (RAI).

3.2. Step 2: Identify climate change impacts on health

Climate change negatively affects human health and well-being in several ways: the frequency and intensity of extreme weather-related events, such as heat waves, floods, droughts and cyclones are growing in large areas of the globe, directly causing illnesses, injuries and deaths, and also indirectly modifying the transmission of waterborne, zoonotic, and foodborne infectious diseases *(48)*. Those who live in the most vulnerable areas, such as small islands, least developed countries, the Arctic, and low-lying regions are at higher risk, but several more countries are experiencing climate-induced water and food scarcity, resulting in forced migration and other dynamics that are likely to further exacerbate health impacts *(48)*.

In this report we consider health impacts originating from extreme weather events (related to short-term weather conditions) as well as in medium-to-long term climate patterns (e.g. delayed start of the rainy season, sea surface temperature warming and acidification). Extreme events include heat waves, floods, droughts, hurricanes and cyclones. We consider both health and infrastructure impacts (e.g. on buildings and health facilities (see Box 4 for more detail), energy, water and transport infrastructure).

3.2.1. Temperature

Heat waves can be defined as hot outdoor temperatures that are beyond the normal range of air temperatures, and that last for several days *(5)*. Health impacts of heat waves include exhaustion, cramps, syncope, strokes, kidney disorders, psychiatric illness, chronic pulmonary illness, diabetes, diarrhoea and cerebrovascular accidents (see Annex 1). Heat waves are also related to vector-borne diseases *(49)* (Box 3), as well as diarrhoea induced by temperature increase *(50)*. In short, heat waves can considerably increase mortality and morbidity among any population. In the past decade, several heat waves have produced devastating effects. For instance, in 2003 the European heat waves killed tens of thousands of people, while the 2010 Russian heat waves were responsible for at least 50 000 deaths *(5)*.

Box 3. Focus on vector-borne diseases

Climate change is expected to modify the geographical range of the habitat of animal vectors of diseases, especially in Asia, Africa and South America *(51)*. For example, malaria is one of the most concerning climate-sensitive vector-borne diseases since a shift in the hospitable geographical range of the Anopheles mosquito could put more people at risk. This is also true for other illnesses transmitted by mosquitoes, such as yellow fever, dengue fever, chikungunya, and the Zika virus *(52)*.

The impact of vector-borne diseases on human health is significant. For example, WHO estimated in 2012 that more than 620 000 deaths were linked to malaria only *(53)*. With increasing climate change, more areas are becoming suitable habitats for mosquitoes, mainly due to the rise in temperature and precipitation. The links between meteorological drivers and the transmission cycle of a vector-borne disease, or its observed geographical distribution, have been used to generate forecasts on the possible spread of vector-borne diseases. These link future climate change scenarios with other determinants such as gross domestic product (GDP) or urbanization, as indications of socioeconomic and technological development *(53)*. The outputs of those models are however highly approximate and they are impacted by uncertainties in climate projects and future development conditions.

The most used approaches to understand and forecast vector-borne disease risk are usually focused on risk prediction in existing endemic zones, rather than predicting transmission risk in new areas *(54)*. Besides, studies of vector distribution typically use correlative approaches to link species records to environmental data to understand suitability of the habitat. These approaches have also been used to understand the links between historical temperature anomalies and rates of human infections, but they fail to capture the large climate impacts on vectors and hosts' seasonality *(54)*. These complex and interrelated processes can forecast the relative impacts of climate change on vector-borne incidence outside endemic zones.

It is expected that, as global warming continues, there will be an increase in the frequency and severity of heat waves. By 2100, extreme heat waves could kill as many people as all infectious diseases combined *(55)*. Globally, in the RCP8.5 scenario, a case with increasing emissions and high global warming, heat waves will be responsible for an additional 73 people dead per 100 000 by the end of the century, with some of the poorest and hotter countries in the world, such as Pakistan and Sudan where the mortality rate could exceed 200 deaths per 100 000 people. It is possible to estimate the health impacts of heat waves by analysing the historical data on temperature as well as the mortality and morbidity records, assessing future impacts using regional climate projections *(55)*.

One of the most important economic impacts of heat waves is lost productivity. Globally, around 2% of total working hours are projected to be lost every year due to higher temperature *(56)*. It is expected that lost productivity will amount to more than US$ 4 trillion annually by 2030, impacting developing countries in particular. It is possible to estimate the impacts of heat stress on lost productivity by combining climate models and global temperature projections with occupational health data and future labour force projections *(57)*. In other words, the impacts on productivity can be assessed through a combination of data and models that highlight the relationship between heat exposure and physiological response, calculating the number of working hours lost per worker for every level of physical impact.

3.2.2. Floods

It has been assessed that extreme rainfall changes could increase urban flooding over a range of up to 400% by the end of the century *(12)*. Such an evaluation is particularly relevant since, for the first time in history, more than 50% of the human population lives in cities, many of which are located along rivers and coastlines, increasing the share of urban areas exposed to flooding *(58)*. In Europe for example, the total urban zones exposed to flooding have increased by 1000% over the past 150 years, with similar trends being observed in Africa and Asia.

In general, floods will increase if the drainage system is not able to cope with the amount of surface runoff produced by climate-induced extreme precipitation *(59)*. The annual global economic costs of floods have been estimated to almost US$ 37 billion annually *(60)*. From the health perspective, the number of people affected every year is almost 35 million globally, which means that floods are the most impactful climate-induced extreme events *(61)*. Sea level rise also exacerbates the impacts of storms (storm surges). Kulp and Strauss (2019) *(62)* indicated that South-East Asian nations are particularly at risk of sea-level rise, by 2050. In particular, more than 20 million people in Viet Nam and 10% of Bangkok's population are at risk. This number is likely to increase since the study did not consider future population growth as well as coastal erosion.

The impacts of floods on human health include drowning, injuries and hypothermia *(63)*. Other health risks are related to evacuation of patients, loss of health workers, and of health infrastructure such as essential drugs. Medium-term implications include infected wounds, poisoning, affected mental health, communicable diseases and starvation. In the long term, chronic diseases and poverty-related diseases such as malnutrition can impact severely on the affected population. Floods can also be responsible for the emergence of waterborne diseases, as well as for the destruction of key infrastructure that in vulnerable areas can increase the displacement of refugees and dislocated people *(59,64)*.

The assessments of health impacts from flooding events are usually modulated by the topographical distribution of population and from social aspects of vulnerability, such as the quality of housing *(65)*. Without detailed information, an *a priori* analysis can be carried out considering climate data such as the monthly rainfall exceeding the baseline. Such a difference can provide information on the frequency of extreme events under specific climate scenarios, while in the geographical information system (GIS) software it is possible to overlay those scenarios over maps of local/global population, to assess health vulnerability.

3.2.3. Droughts

Eighty per cent of the global population is already experiencing some type of water insecurity *(12)*. Forecasts are not encouraging. For example, droughts are expected to increase in some regions of the world, such as the Mediterranean and West Africa *(52)*. On many small island developing States, freshwater stress is expected to worsen due to declining precipitation going forward. An increasing number of urban populations are estimated to be impacted by severe droughts in central and southern Europe, North and West Africa, and South-East Asia *(66)*. Health impacts of droughts are primarily related to the negative effects that droughts have on soil moisture levels, resulting in crop failure and reduced agricultural output, which contributes to malnutrition. Temperature and precipitation trends have already reduced crop production and yields, especially wheat and maize *(67)* (Lobell, Schlenker, & Costa-Roberts, 2011). Lower production of food in many of the poorest and most vulnerable regions will increase malnutrition and undernutrition, which currently cause more than 3 million deaths annually *(68,69)*.

Vulnerability to drought can be based on three general methods *(70)*:

- Based on the mapping of agro-ecological activities, where the effects of droughts on local ecosystems are identified. However, these maps are often qualitative and fail to provide a value of potential impacts.
- Based on the involvement of community groups to document the effects of droughts. For example, in Kenya qualitative findings generated with this method have been compared to quantitative data on household characteristics generated via programmes such as the Hunger Safety-net Programme and with data on child nutrition, supporting the validation of the method.
- Based on the assessment at the basin/catchment level, accounting water resources and assessing exposure to drought risks due to water scarcity,

3.2.4. Extreme weather events

The most frequent impacts of extreme events on human health include deaths, physical injuries, mental health issues, water and food scarcity, water- and vector-borne diseases, forced migration and damage to health facilities *(71)*.

Hurricanes and tropical storms have serious consequences on the economy, environment and human health. For instance, Hurricanes Florence and Michael and Typhoon Mangkhut were responsible for hundreds of deaths and caused billions of economic damage *(72)*. The severity and intensity of tropical cyclones are expected to increase due to climate change *(73)*. Specifically, the severity of storm surge events is expected to increase due to sea-level rise and population growth *(74)*, and mortality is expected to increase as well if no action is taken *(12)*, especially in East Asia, one of the most vulnerable areas in the world *(75)*.

It is expected that by 2100 between 230 and 250 million people will be at risk due to future storms in China and South-East Asia alone *(76)*. Economic impacts are also serious: it has been estimated that storm-related costs in the United States of America between 1980 and 2017 exceeded US$ 1.3 trillion *(73)*.

The health impacts of extreme events depend on several factors, such as the physical impacts themselves, and the socioeconomic and environmental contexts at the time and place where they occur *(77)*. These aspects can exacerbate or mitigate health outcomes and vulnerability in the affected population and individuals.

Considering climate change, few comprehensive or systematic studies have investigated the health consequences of such health-system strain *(77)*. For example, in the context of hurricanes, the impacts on health systems from population displacement are not yet fully understood. Methodological challenges for quantifying and attributing mortality associated with (but not caused directly from) extreme events exposure remain. Thus, future assessment can benefit from research activities that will study health outcomes of secondary effects of extreme events (such as disruption of hospitals), examine the health implications associated with particular extreme events such as floods and droughts, and improve the understanding of health impacts after extreme events, including behavioural and social responses.

3.2.5. Sea surface temperature and acidification

The CO_2 emissions absorbed by oceans are increasing water acidity: it has been estimated that since the beginning of the industrial revolution the ocean pH has increased by 26% *(12)*. In 2018, many areas of the world's oceans experienced warmer-than-usual sea surface temperatures, with negative consequences on local ecosystems *(72)*. Higher sea surface temperature and ocean acidification can reduce the ability of some organisms, including molluscs and corals, to maintain basic functions. Besides, there is growing evidence that fish stocks and fisheries production are decreasing in low- and mid-level latitudes due to increasing temperature and ocean acidification *(72)*. Declining fisheries and compromised ocean ecosystems mean that coastal communities that depend directly on the health of marine environments are affected. For instance, it has been estimated that around 3 billion people depend on fish products for 20% of their annual protein intake, which may be compromised by different factors including climate change.

Understanding the links between ocean warming and acidification on human health involves a high degree of complexity, making it difficult to comprehend and manage *(78)*. Initially, studies of ocean warming and acidification focused mainly on potential effects, such as the impact of pH on calcifying organisms. Nowadays, research is more focused on the complexity of indirect effects at the ecosystems level. For example, the effects of CO_2 are known to modify the availability and nutritional value of primary producers in the food chain, as well as their toxicity to humans. Therefore, ocean acidification can be considered an emerging human health issue of great complexity.

Ocean warming and acidification have the potential to affect the nutritional values of the available seafood, leading to a reduction of lipids and proteins in some species *(78)*. Such a reduction is relevant from a human health point of view, given their importance (e.g. polyunsaturated fatty acids like omega-3 are widely known to be beneficial to human health).

Box 4. Focus on climate impacts on health facilities

- Climate risks to health care facilities are associated with extreme weather events, heat and high temperature, droughts, flooding or excessive rainfall, winds or storms *(79)*.
- Climate change impacts on health care facilities may include *(80)*:
  - For heatwaves, crowding of hospital facilities in Australia by people taking advantage of air conditioning; overheating and failure of computer systems; overheating of electricity supply and appliances; and water shortages;
  - For floods, electrical power outages; access problems for staff; an actual case of emergency evacuation due to floods in the United Kingdom of Great Britain and Northern Ireland;
  - For storm surges, potential destruction of facilities and access roads; in Australia, actual closure of one hospital and power outage and leaking roofs at another hospital resulting in emergency evacuation;
  - For tsunamis, actual destruction of hospitals as in Indonesia in 2004; loss of equipment and medical records in the Maldives; access difficulties.
- Climate hazards can impact health workers' mental health *(79)*.
- Health care facilities can respond to the climate challenge by becoming more resilient to climate stressors and reducing their GHG and pollutant emissions *(79)*. Additional planning and coordination are needed to address health facilities' vulnerability to climate change (Carthey & Chandra, 2007). According to Weaver et al. (2010) *(81)* education and training of health care workers at all levels need to take into account the projected health impacts of climate change.
- Climate change can also affect traditional health care practices. Maikhuri et al. (2018) *(82)* suggest that climate change has negatively affected such practices in high-altitude mountain regions by disrupting the growth of, and access to, medicinal and aromatic plants.

3.3. Step 3: Identify intervention options – climate change mitigation and adaptation

This section identifies the main intervention options available to reduce emissions and improve climate resilience. Since models are normally designed and utilized to inform decision-making, this summary focuses on the types of intervention option that models could analyse, e.g. the outcomes of achieving a given target as opposed to the outcomes emerging from the implementation of a given policy instrument, both for climate mitigation (Table 1) and adaptation (Table 2).

These tables indicate the causal pathways that characterize each intervention option, highlighting direct, indirect and induced impacts of policy implementation. We find that health impacts of climate mitigation and adaptation are either indirect (primarily for adaptation) or induced (primarily for mitigation). On the other hand, there are climate mitigation and adaptation actions that directly impact health (e.g. health warning systems), as well as operations in the health sector (e.g. access to reliable power supply avoids disruptions in service delivery and reduces mortality). This partly explains why health considerations are normally not made in the formulation and evaluation of climate mitigation and adaptation policies in health- and non-health-determining sectors, being distant from the direct and expected outcomes of policy implementation.

Information on indicators and causality is important for the identification and selection of useful simulation models, i.e. to identify whether the models identified for carrying out the assessment (considering that models are a simplification of reality) capture the desired indicators and use a similar causal pathway as our observations of reality. This information is also useful to interpret model results.

More details on specific areas of analysis can be found in the existing literature, e.g. Hunt for air and water pollution (2011) *(83)*, Wilkinson for mitigation (2010) *(84)*, WHO for adaptation (2013) *(10)* and Pongsiri et al. for the need to take a systemic approach to policy analysis (2021) *(85)*.

Table 1. Overview of climate mitigation options, their direct, indirect and induced impacts

	Direct impacts	Indirect impacts	Induced impacts
Mitigation			
Energy	Reduction of fossil fuel use via (i) energy efficiency and (ii) fuel switching	Reduction of air pollution and of climate change	Reduction of respiratory diseases, cardiovascular damage, cancer, fatigue, headaches and anxiety, irritation of the eyes, nose and throat, damage to reproductive organs, nervous system damage. Improvements in mental health due to improved well-being.
Waste	Reduction of waste generation, reduction of waste landfilled via improved collection, sorting, treatment, recycling and reuse	Reduced air, soil and water pollution and the related impacts on climate change	Reduced cancer, lymphoma, malformations, mortality; reduced impacts on reproductive organs, well-being. Improvements in mental health through improved well-being.
Agriculture and livestock	Reduction of fertilizer use, increased land productivity, improved animal production and related quality	Reduced soil erosion and water pollution; reduced risk of floods and landslides, and reduced vulnerability to droughts	Decreased respiratory, dermatological and neoplastic hazards. Decreased risk of antibiotic resistance. Reduced impacts on nutrition.
Land use, land-use change and forestry (LULUCF)	Reduced deforestation and forest degradation, increased forest cover and agroforestry production	Increased water availability and water quality, also higher soil quality for improved land productivity; improved CO_2 stocks	Protection of key ecosystem services for human well-being (e.g. water) and avoided impacts on human health (e.g. floods, fires). Improvements in mental health due to improved well-being.
Industrial processes and product use (IPPU)	Reduction of fossil fuels for feedstock energy use, reduction in the use of carbon-intensive materials in the production process	Reduced air and water pollution and climate impacts related to these as well as to reduce fossil fuel consumption	Reduced respiratory and cardiovascular illness, toxicity, nervous system effects, and skin and respiratory illness. Improvements in mental health due to improved well-being.

Table 2. Overview of climate adaptation options, their direct, indirect and induced impacts

		Direct impacts	Indirect impacts	Induced impacts
Adaptation				
Land	**Agriculture**	Resilient crop production, with drought-resistant crops and improved soil quality	Higher production (or reduced losses), improved food security and nutrition; higher carbon sequestration	As a result of improved nutrition, stronger labor force, increased production and income, as well as public revenues, while public spending declines. Increased revenues, higher affordability of healthy diets. Improvements in mental health due to improved well-being.
	Forestry	Increase in forest cover	Increased water retention, water filtration and higher production of non-timber forest products (NTFP)	Reduced burden of disease and of mortality and morbidity driven by reduced risk of floods and heat waves. Improvements in mental health due to improved well-being.
Health		Improved preparedness and more efficient delivery of health services; more knowledgeable and trained personnel	Improved human health, higher labour productivity; reduced risk and severity of extreme weather events such as droughts and floods; reduced cost of service delivery	As a result of improved health, stronger labor force, increased production and income, as well as public revenues, while public spending declines (e.g. reduced risk of failing infrastructure). Improvements in mental health due to improved well-being.
Water		Increased water availability and water quality; improved water treatment	Reduced risk of water and food scarcity; reduced cases of diarrhoea, skin and tissue infections, dysentery; reduced morbidity and mortality from vector-borne diseases	As a result of improved access to clean water and sanitation, stronger labour force, increased production and income, as well as public revenues, while public spending declines (e.g. reduced cost of visits and treatment). Improvements in mental health through improved well-being.
Infrastructure		Continued service delivery, with no interruptions due to infrastructure damage; cost-effective operation of infrastructure	Improved well-being, reduced mortality and morbidity	Reduced economic impact of infrastructure damage, lower spending for fixing infrastructure damage. Increased production (e.g. via higher access to markets for farmers) and income, as well as public revenues. Improvements in mental health due to improved well-being.

3.3.1. Climate change mitigation

This section identifies the main carbon emitting sectors (i.e. the largest opportunities for emissions reduction), and outlines the main potential health effects of climate mitigation action in these sectors.

Climate mitigation action can be implemented in several sectors. The types of policies and actions implemented can have an impact on health per se, in addition to the impacts that they intend to have on climate change reduction, which should also turn into health impacts as discussed in section 3.2. This report focuses on policies and actions related to energy production and consumption (e.g. in buildings, transport), waste generation and waste management, agriculture and livestock practices, land use and land cover change, and industrial processes. While acknowledging that policy entry points are often sectoral (e.g. power generation, transport policy), we adopt the same classification of emissions used by the Intergovernmental Panel on Climate Change (IPCC) and included in the United Nations Framework Convention on Climate Change (UNFCCC) guidance for the creation of national GHG inventories. This ensures consistency between GHG sources and sinks and policy interventions, as outlined in the nationally determined contribution (NDC). NDCs include non-binding national targets and plans for emission reduction. The following subsections present the incidence of each sector in the generation of GHG emissions at the global level, followed by examples of investments that can be implemented to reduce emissions.

Energy

The energy sector has been responsible for around 40% of global CO_2 emissions in the past decade *(86)*. Around 75% of those emissions are produced by the six largest world economies. In particular, coal power plants accounted for 30% of all energy-related emissions in 2019 *(87)*. Burning fossil fuels for generating electricity impacts the health of local communities and global population since it contributes to both air pollution and global climate change *(88)*. Air pollution is a relevant risk factor for different diseases, especially cardiovascular and respiratory diseases, and cancer, being responsible for 3 million premature deaths per year *(12)*. Although air pollution is mostly a local factor, there are also cross-border effects.

The most common polices for climate change mitigation in the energy sector include energy efficiency measures and renewable energy technologies (fuel switching, e.g. via electrification, use of hydrogen) *(89)* that can reduce GHG emissions from fossil fuels combustion, also improving access to electricity and eventually positively impacting socioeconomic development, and human health *(4)*. Mitigation strategies in the energy sector vary by region; e.g. Europe has a strong focus on phasing out coal, while China and India's NDCs would need to be strengthened to address emissions from coal usage *(15)*.

Waste

If not appropriately disposed of or reutilized/recycled, waste can significantly contribute to GHG emissions from incineration, fires and food decomposition *(90)*, contributing to 5% of global carbon emissions in 2016 *(91)*.

Interventions include prevention measures, including supporting communities to use materials that do not produce waste *(92)*; recycling, reusing and composting, allowing to re-use materials and avoiding the need for landfills, which are a significant source of GHGs *(93)*. Such measures are particularly relevant in the context of future trends: it is expected that waste-related emissions will grow from the current 1.6 billion tonnes of CO_2 equivalent to 2.6 billion tonnes of CO_2 equivalent by 2050 *(91)*. Most of these emissions will be generated in developing countries, which are already the most impacted health-wise.

Agriculture and livestock

The food systems, including production distribution, consumption of food, significantly contribute to climate change: agriculture, together with forestry and other land use activities, represents around 13% of CO_2 emissions, as well as more than 40% and 80% of methane and nitrous oxide emissions, respectively. In other words, agriculture, forestry and other land use (AFOLU) activities represent around 23% of all anthropogenic GHG emissions *(94)* Moreover, this figure can increase up to 37% of the total net anthropogenic GHG emissions when also considering emissions from global food systems *(94)*.

Additionally, agricultural and livestock production produces toxic gases, vapours, particles that are emitted into the environment contaminating land, air and water, and ultimately affecting human health (increasing respiratory, dermatological and neoplastic hazards) *(95)*. Moreover, because large numbers of animals are kept in crowded conditions, antibiotic resistance can arise, leading to treatment failure, resulting in chronic problems *(96)*.

Climate-smart agricultural (CSA) practices can increase productivity and also reduce GHG emissions *(97)*. Other practices, such as crop residue management, organic fertilizers and agroforestry can considerably increase the stocks of soil organic carbon (SOC); composting crop residues and adding them to the field can reduce methane emissions in rice fields *(98)*. Mitigation practices that improve productivity can also be applied to the livestock sector. In this context, the goal is often to improve livestock productivity, increasing emissions per animal head but reducing total emissions in the sector *(98)*. For example, pasture management can modify enteric methane emissions from livestock by improving the quality and/or availability of fodder. Improved pasture typically increases emissions per head, but it also increases productivity, which means that emission per unit of meat or milk production decreases. A decrease in the intensity of emissions can lead to a decline in absolute emissions if followed by a reduction in the size of the herd *(98)*.

Land use, land-use change and forestry

Forests cover around 35% of the global surface and absorb approximately 30% of all anthropogenic emissions annually *(99)*. Nevertheless, forest degradation due to drivers such as forest fires, timber and wood fuel harvest is responsible for the emission of more than 2 billion tonnes of CO_2 *(100)*. Overall, CO_2 emissions from land use, land-use change and forestry (LULUCF) represent 12% of global emissions *(101)*.

Forest loss can result in negative consequences for human health. For example, in Brazil, approximately 15% of the Amazon rainforest was destroyed for agricultural purposes between 1975 and 2000 *(102)*. The majority of forest loss occurred using fires, which increased particulate matter concentration in the air, increasing local mortality and cases of hospitalization.

The increase of climate-driven forest disturbances, such as fires, affects the ability of forests to provide key ecosystem services to society, such as water supply and water purification, food production and climate mitigation *(103,104)*. Therefore, climate change impacts on LULUCF call for strategies and approaches that can improve resilience to ensure the delivery of those ecosystem services that are essential for human health and well-being *(103)*. Available intervention options include reducing deforestation (including investments to reduce its causes, e.g. improved agriculture productivity), reforestation and afforestation, with the dual goal to reduce emissions and improve and protect human health.

Industrial processes and product use

The industrial sector represents around 27% of global GHG emissions, using approximately 40% of the energy produced *(94,105)*. In recent years, industrialization in developing countries has skyrocketed, thanks to low production costs and institutional flexibility *(106)*. As a consequence, labour-intensive and environmental-polluting industries have been relocated to those countries with the only goal to maximize profits, with little or no regard to local socioeconomic impacts and global emissions. Some of the negative consequences of industrial production on human health include waterborne diseases, respiratory and cardiovascular illness, toxicity, nervous system effects, and skin and respiratory illness *(106)*.

A wide range of options are available to reduce the negative impacts of the industrial processes and product use (IPPU) sector on human health. First, energy efficiency technologies can support the optimization of production processes, decreasing emissions and energy demand *(12)*. Second, fuel switching can reduce total emissions, as in the case of switching from coal to renewables for heat, water and electricity. Finally, industrial emissions can also be reduced by decreasing the demand for products, and/or by improving product design and production (i.e. the manufacturing process).

3.3.2. Climate change adaptation

A review of 20 national adaptation plans (NAPs) found that around 10% of all the actions considered are health actions (excluding health-related measures in other sectors) *(107)*. Health actions in NAPs are frequently addressed to combat vector- and waterborne diseases (68% and 58%, respectively), health impacts of extreme events (53%), and climate-resilient health facilities (53%). Only 5% of NAPs (just one) includes actions to fight mental and psychological health risks. The adaptation components that are most frequently prioritized in NAPs are integrated risk monitoring and early warning (89%), and health workforce (84%). On the contrary, only 32% and 37% of NAPs prioritize "management of environmental determinants of health" and "climate health and financing", respectively.

Building and extending on the review of NAPs, this section identifies the main environmental determinants of health, and outlines the main opportunities for adaptation measures in these sectors to protect/improve health. It provides examples for the type of intervention options that can improve climate resilience and thus result in positive health co-benefits in the following thematic areas: land and food systems, water, infrastructure and health.

Land and food systems

Land-related actions that can contribute to climate change adaptation include, but are not limited to, sustainable food production, SOC management, land restoration and ecosystem conservation, sustainable forest management, and reduced deforestation *(94)*.

Concerning land use, restoring natural wetlands and floodplains to retain surface runoff can improve the state of water and local ecosystems *(108)*, while reducing the risk of floods and droughts. Moreover, adaptation strategies to limit the impacts of heat waves at the urban level include increasing the use of vegetation and trees that can cool air temperature, both outdoor and indoor *(109)* . This results in positive health impacts. For example, according to a study carried out in Washington DC, increasing vegetative cover by 10% could reduce deaths during heat waves by an average of 7% compared to past events, saving approximately 20 lives every 10 years *(110)*. Furthermore, if all costs are included, green infrastructure is cheaper, freeing up resources that can be re-invested in other sectors, such as health. For instance, the city of Philadelphia in the United States found that its new green infrastructure plan will cost more than US$ 1 billion over 25 years, while a grey infrastructure plan could cost six times more during the same period *(111)* , both due to the cost of infrastructure and the cost of providing services (e.g. heating and cooling) with different baseline infrastructure approaches.

Focusing on the agricultural sector, CSA practices can raise crop yields by 7–15%, increasing net income and nutrition *(97)*, more than offsetting the impact that climate change may have on land productivity. Moreover, the use of remote-sensing technologies, data science, and software tools would help to rapidly detect changes that require interventions *(112)*. Furthermore, precision breeding and the improvement of the understanding of microbiomes would help to adapt crop production to climate change impacts.

While some adaptation options produce immediate impacts, other strategies need years to produce measurable results *(94)*. Examples of long lag-time include the conservation of high-carbon ecosystems such as mangroves and peatlands, as well as afforestation, restoration and agroforestry measures. This indicates that while some health benefits may emerge in the short term, more are expected to emerge in the medium and longer term.

Water

Support to water, sanitation and hygiene (WASH) services should continue to counter the growing health and other impacts of climate change *(113)*. Opportunities include the use of smart technologies that can improve measuring water quality and identify suitable options for intervention. Adequate strategies and processes (e.g. climate-resilient water safety planning) and infrastructure are also key measures.

Overall, a wide range of technology options can be used for improving both water quality and availability *(114)*. These include wastewater reclamation technologies at the domestic level, rainwater harvesting solutions (such as tanks and cisterns), desalination through thermal evaporation or membrane separation, natural solutions to treat wastewater such as wetlands, and other technologies for water treatment, like sand filtration, chemical coagulation, membrane filtration, precipitation, neutralization, oxidation, hydrolysis, reverse osmosis, granulated organic carbon filters; disinfection through chlorination, ozonation, ultraviolet (UV).

Infrastructure

Extreme weather events are expected to increase in frequency and intensity, causing damage to infrastructure, and hence human health and economic activity *(59,115)*. For example, if drainage systems are not able to contain the surface water runoff generated by extreme precipitation, floods will occur, with possible damage to infrastructure, resulting in economic activity being halted, investments to fix infrastructure being required (using resources that could have been destined for other activities), and increasing the risk of waterborne diseases *(59)*.

Generally, infrastructure is often not designed to cope with extreme events, or not of the size that climate change will carry. Resilient infrastructure is needed, both to ensure continued service and to reduce the maintenance cost. This implies not only building or rebuilding infrastructure, but also deciding if infrastructure is needed (e.g. there may be viable nature-based solutions that could replace the need for new built infrastructure), and where it should be built.

More specifically, and to provide an example, flood risk reduction strategies fall into two categories: structural and non-structural *(116)*. Structural forms can reduce harm by reconstructing landscapes, such as floodgates, seawalls and evacuation routes. Non-structural strategies, such as elevated structures, building codes and zoning, mitigate damage by removing people and infrastructure out of risk areas. The right mix of measures can differ depending on location, funding and political will (Jongman, 2018). Physical flood protection measures, such as dikes and levees, are generally cost-effective in areas with a high density of population *(58)*. For example, the Netherlands, a highly populated and flood-prone country, widely uses structural measures, such as a vast dike system that can protect against events that can occur once every 10 000 years.

Climate resilience for infrastructure can be achieved by ensuring high efficiency in the delivery of services (e.g. energy and water efficiency), independence in the provisioning of such services (e.g. via roof-mounted solar panels, via the use of water recycling in buildings), and low vulnerability to external events (e.g. with infrastructure being located in areas that are not flood-prone or subject to storm surges). The use of local materials and construction practices, combined with the consideration of risks related to extreme events (e.g. one in 100 or one in 200 years) is likely to improve climate resilience of infrastructure.

Health

Preparing the health sector to climate change impacts requires improving the understanding of climate–health relationships and delivering adequate financial resources *(117)*. In this context, health information systems, climate-resilient infrastructure and capacity building are key areas of investment for a climate-resilient health sector.

Health information systems are required to inform decision-makers on climate risk and vulnerability; they increase climate preparedness as well as enable the development of EWS *(118)*. However, developing countries may not have the possibility to integrate health information systems into national strategies due to a lack of knowledge and financial resources *(119)*.

Increasing the climate resilience of health care would allow to maintain effective operations during disasters and extreme weather events, which is when health services are most required. Further, climate-resilient operations are less costly *(120–122)*, allowing to avoid power cuts (e.g. with renewable energy *(123)*), water shortages, wind damage and more. Hospitals and other health infrastructure should be able to operate with no interruption to guarantee the protection of their patients, also delivering key health services following natural disasters *(124)*, as also discussed in case study 6 (see section 5.6). Commitment towards this goal was confirmed at 26th United Nations Climate Change Conference (COP26) in November 2021, in relation to the need to develop "Climate-resilient and low carbon sustainable health systems". Two main areas of work have been identified: (i) climate-resilient health systems, including the preparation of climate change and health vulnerability and adaptation assessments, the formulation of a health national adaptation plan (HNAP) informed by the health vulnerability and adaptation, the use of the vulnerability and adaptation and HNAP to facilitate access to climate change funding for health; and (ii) sustainable low carbon health systems, including setting a target date by which to achieve health system net zero emissions, delivering a baseline assessment of GHG emissions of the health system (including supply chains), and developing an action plan or roadmap for low carbon health systems that also considers human exposure to air pollution and the role the health sector can play in reducing exposure to air pollution through its activities and actions.

Finally, the training of health care personnel, from nurses to medical students, would help to expand the professional and practical knowledge of climate change impacts on human health, improving effectiveness in diagnosing and treating diseases *(125,126)*. Training courses and raise-awareness materials would help highlight the interlinkages between health and climate change, also suggesting appropriate tools and actions.

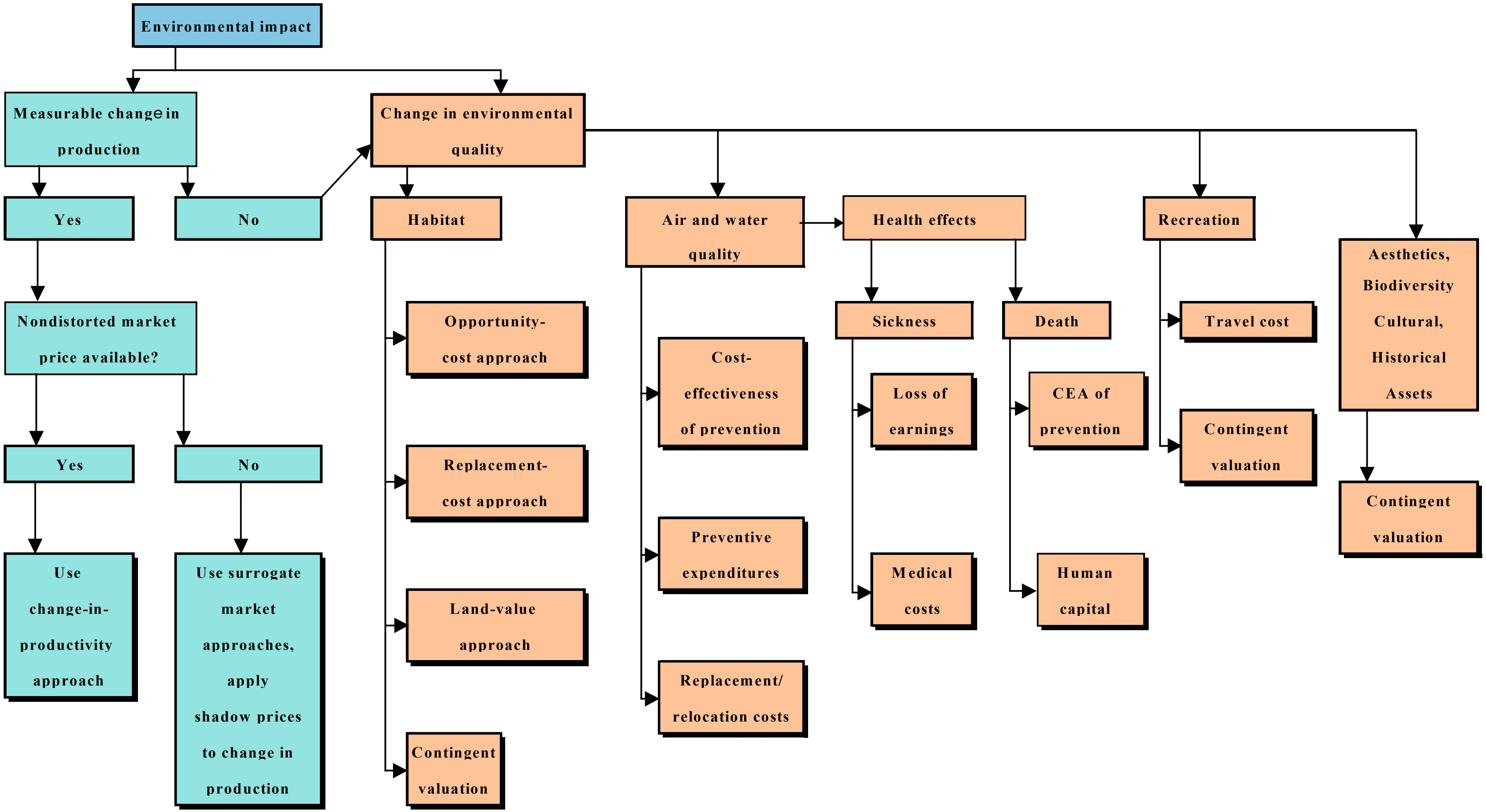
3.4. Step 4: Identification and selection of relevant indicators for economic analysis

This section presents the main indicators required to carry out an economic analysis of the health impacts identified in previous sections. As indicated above, the estimation of the cost of health impacts starts from the identification of indicators that represent the cause of such impacts, in a physical unit. Then indicators representing effects are identified next. Both causes and effects may be social, economic or environmental, and belong to different sectors. As a result, the identification of relevant indicators has to follow a systemic approach *(127)*, as does the framework presented in section 2.

Table 3 presents health impacts, indicators and methods for economic valuation, and reference studies that provide information in such methods and case studies. For each key health impact area presented, there is a method for estimating (i) the cost of inaction and (ii) the cost of action (i.e. to avoid the health impact). These two approaches are considered because, as presented in Fig. 2, they provide inputs to different stages of the decision-making process, and to different processes in different sectors. The cost of inaction is useful to raise awareness and stimulate action, especially in the health sector. The cost and benefits of action are useful to formulate a strategy and prioritize action, especially in non-health sectors where the health co-benefits may increase the attractiveness of a given intervention versus others.

The literature indicates that the more immediate and direct the impact is, the easier it is to quantify and monetize such impact *(128)*. This poses challenges for the estimation of the economic evaluation of health outcomes of climate action, given that, as shown in Table 1 and Table 2, most of the health outcomes are either indirect or induced. As an example, Fig. 4 shows a chart of valuation methodologies and suggests which approaches are the most useful when dealing with air and water quality changes. Concerning health effects, sickness (morbidity) and mortality are mentioned. The former can be monetized using loss of earnings from sick leave and medical costs. The latter can be valued using cost–effectiveness estimates of preventive actions and loss of life (e.g. value of statistical life [VSL]) *(128)*. The figure also stresses that, to quantify the economic damage or cost of interventions, it is essential to assess indicators related to the causes of health effects, in this specific case air and water quality. Prevention and replacement costs are indicated as viable options for the economic valuation of air and water quality (e.g. the use of sustainable agriculture practices could be used to reduce pollutant loading, or investment in water treatment facilities could be considered to remove pollutants form water bodies). Other methods for economic valuation are proposed for other types of environmental impacts. Some are price-based (when there is a market price for goods and services), while others are preference-based (e.g. contingent valuation, which is based on willingness to pay).

Fig. 4. Valuation flowchart *(128)*



As indicated above, the tasks required to perform an economic valuation pertain primarily to the estimation of the level of exposure, forecasting changes in health outcomes and assigning an economic value to such change. For instance, for morbidity, the most used approaches rely on data on loss of earnings and medical care costs. However, for mortality, the problem of validation is more challenging: no universally agreed upon technique is available on the cost-effectiveness of preventing deaths (e.g. VSL is often used, although its calculation and meaning are not trivial) *(129)*. In a recent work discussing VSL in the context of another large-scale global challenge, COVID-19, Colmer (2020) *(130)* outlines the following challenges: increased mortality risks beyond the normal range estimates may result in an underestimation of social benefits of risk response; different risk profiles from those typically used in VSL estimates; and different population profiles than those populations for whom VSL estimates were developed.

Table 3. Summary of the approaches available to estimate the cost of health impacts, or the investment required to avoid them

Health impact	Economic valuation indicators	Reference
Air pollution–mortality and morbidity impacts	***Inaction*:** Estimation of fossil fuel use, resulting concentration of air pollutants. Determination of mortality and morbidity through increased incidence of related diseases, using dose–response functions and then estimating health care costs (e.g. treatment of relevant health conditions), or estimating the value of statistical life (VSL) for mortality, or willingness to pay (WTP) for morbidity. Both a top–down (macro) or bottom–up (micro) approach can be used for the economic valuation. Also, both public and private spending for health should be considered, to estimate the current and future burden on government and households.	*(9,83,91)*
	***Action*:** Savings from the removal of fossil fuel subsidies; investments in energy efficiency (e.g. using US$ per MWh of electricity avoided) and fuel substitution (e.g. renewable energy, kerosene to liquefied petroleum gas [LPG], etc.) (e.g. using US$ per MW of power generation capacity) required to reduce air pollution to a desired target. Use the investment to assess the extent to which fossil fuel consumption is reduced, and resulting impact on air pollution and burden of disease, and hence on avoided health costs.	*(91,131)*
Infectious diseases from air, water and food	***Inaction*:** Determination of mortality and morbidity; then estimation of health care costs (e.g. treatment of relevant health conditions) and potential loss of income; or estimation of the VSL or WTP. Both a top–down (macro, for estimating potential loss of gross domestic product [GDP]) or bottom–up (micro, for household economics) approach can be used for the economic valuation.	*(83,132)*
	***Action*:** Estimation of the cost of reducing air and water pollution (e.g. via energy efficiency, fuel switching, introduction of wastewater treatment facilities) and of the substitution of harmful land-use practices with sustainable ones (e.g. limiting the use of chemical fertilizers). Savings from avoided morbidity and mortality, emerging as reduced private and public health care costs, and higher economic activity should be compared with the cost of action in a cost–benefit analysis (CBA).	

Health impact	Economic valuation indicators	Reference
Parasitic and vector-borne diseases	***Inaction***: Estimation of mortality and morbidity; then estimation of health care costs (e.g. treatment of relevant health conditions), possible cost of relocation and potential loss of livelihood and income; or estimation of the VSL or WTP. Also in this case, both a top–down (macro, for estimating potential loss of economic activity) or bottom–up (micro, for household economics) approach can be used for the economic valuation.	*(53)*
	Action: Estimation of the number of people and area at risk, also in relation to changing climatic conditions. Cost of surveillance, prevention and control of diseases (e.g. purchase and distribution of mosquito nets, investment in nature-based solutions related to afforestation and reforestation and wetland management, investment in health information systems).	
Health impacts from extreme weather events and natural disasters	***Inaction***: • *Direct*: estimation of the number of people affected by an extreme weather event, estimation of the cost of treatment and support required (e.g. in relation to medical treatment) or the cost related to mortality. • *Indirect*: estimation of the infrastructure damaged (e.g. transport, buildings, telecommunication) and of the lost agriculture production (e.g. due to floods). This damage, used in macroeconomic models, can support the estimation of lost GDP and employment. • *Reconstruction*: estimation of the relief and reconstruction budget required, e.g. for nutrition (food aid) and for re-building roads and fixing public and private buildings. This budget estimate could then be used to estimate public deficit and resulting increase in public debt and interest payments.	*(91,133)*
	Action: Estimation of the infrastructure vulnerable to extreme weather events (e.g. transport, buildings, telecommunication) and of the agriculture land potentially affected. Identification of resilient infrastructure options, including new built infrastructure and nature-based infrastructure (NBI) and resilient land management practices. Estimation of the cost of resilient infrastructure, and of the additional co-benefits it would create for the public and private sectors. Estimation of the public cost, impact on government finances in the short term (possibly higher budget for preventive investments) and medium and longer term (possible reductions when compared to a business as usual [BAU] scenario). For health facilities and infrastructure: reduced capacity or inability to offer health care services	

Health impact	Economic valuation indicators	Reference
Indirect human-mediated health impacts (e.g. nutritional deficiencies, mental health conditions, occupational health, violence and conflict)	***Inaction***: • *Direct*: estimation of the number of people affected by food availability, low food quality, affected productivity, mental illness, psychological distress and poverty. • *Indirect*: estimation of the factors affecting nutrition (food prices changes, energy costs), occupational health (air temperature). Indirect mental health impacts can arise from extreme weather conditions that may produce negative effects on those with mental illness through the impacts on economic activities (e.g. fishing, forestry). Environmental and socioeconomic factors, such as soil degradation or poverty, can influence conflicts and violence.	*(134–136)*
	Action: Identification of intervention options that can both increase preparedness and reduce indirect human-mediated impacts. For instance, in the case of nutrition, climate-smart agriculture (CSA) for land productivity and production as well as improved distribution to reduce food losses and increase access. In the case of mental illness and psychological distress, investments in vulnerability mapping, climate information services and early warning systems (EWS). Estimation of the cost of such interventions, both for the public and private sectors, with an estimation of capital as well as operation and maintenance costs. Estimation of the impact on government finances in the short term (with higher costs) as well as medium and longer term (with operation and maintenance costs as well as cost savings when compared to a BAU scenario for reduced indirect human-mediated impacts).	*(136)*

3.5. Step 5: Identification of suitable methods and models

Estimating the health impacts of climate action is a complex process that needs to involve different disciplines *(11,134,137)*.

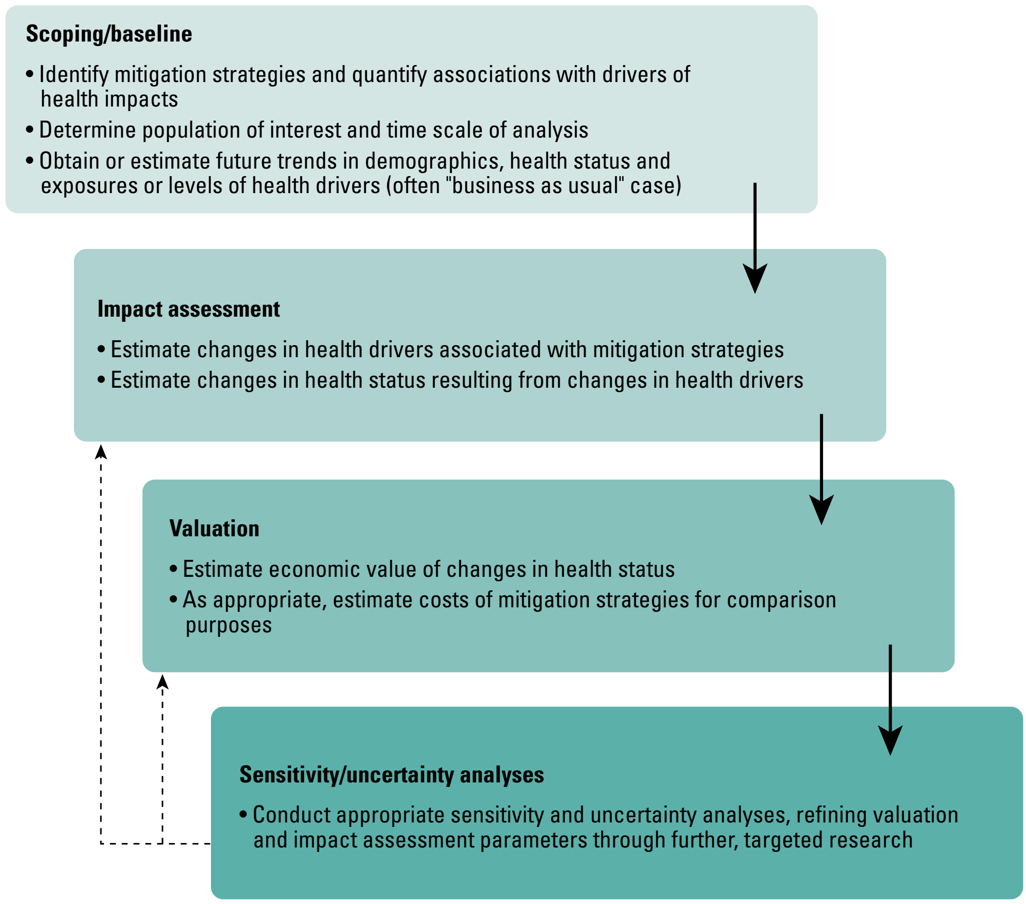
Several methods and models are available for the estimation of health impacts and their economic valuation. We first introduce ST as a method to identify indicators of relevance across sectors, economic actors and dimensions of development. We then introduce and group available models in five main categories: (i) those that support the estimation of the drivers of health impacts (e.g. energy use and air pollution); (ii) those that estimate health impacts; (iii) those that perform an economic valuation of health impacts or estimate the investment required to reduce health impacts; (iv) those that do all of the above, using a nested approach (e.g. linking and using simultaneously two or more models); and (v) those that do all of the above, using a single integrated model.

3.5.1. Understanding complexity with systems thinking

Policy decisions about climate change action are progressively integrating the positive and negative health impacts of low carbon strategies *(137,138)*. Studies evaluating the health effects of mitigation strategies, indicated as "co-benefits" utilize different modelling approaches formulated with health experts from different sectors to provide policy-relevant outcomes. It is worth highlighting that the term "co-benefit" can also include negative impacts.

Documenting such co-benefits can help to deliver more ambitious and health-related climate change mitigation actions *(137)*. Besides, assessing the health effects of mitigation actions can support policy-makers to direct investments based on the expected health benefits of mitigation actions *(138)*. In this context, an expert panel of researchers on health effects of mitigation action developed guidance for such modelling. This checklist, shown in Fig. 5, provides guidelines for piloting and reporting estimates of health benefits of mitigation actions to make them more comparable for policy-makers, potentially helping to strengthen evidence-based decision-making processes *(137)*. It practically highlights the need to use a systemic as well as systematic approach in developing and using models for the estimation of the health cost of inaction and the creation of health co-benefits from climate action.

Fig. 5. General approach for health effects of mitigation models *(137)*



Causal loop diagrams (CLDs) are a powerful tool to identify causality using a systemic approach, anticipate impacts (both desired and undesired) and test the ambition, and possible transformational outcomes is a system map. A CLD is a map of the system analysed, or better, a way to explore and represent the interconnections between the key indicators in the analysed sector or system *(139)* (see Fig. 6 for an example).

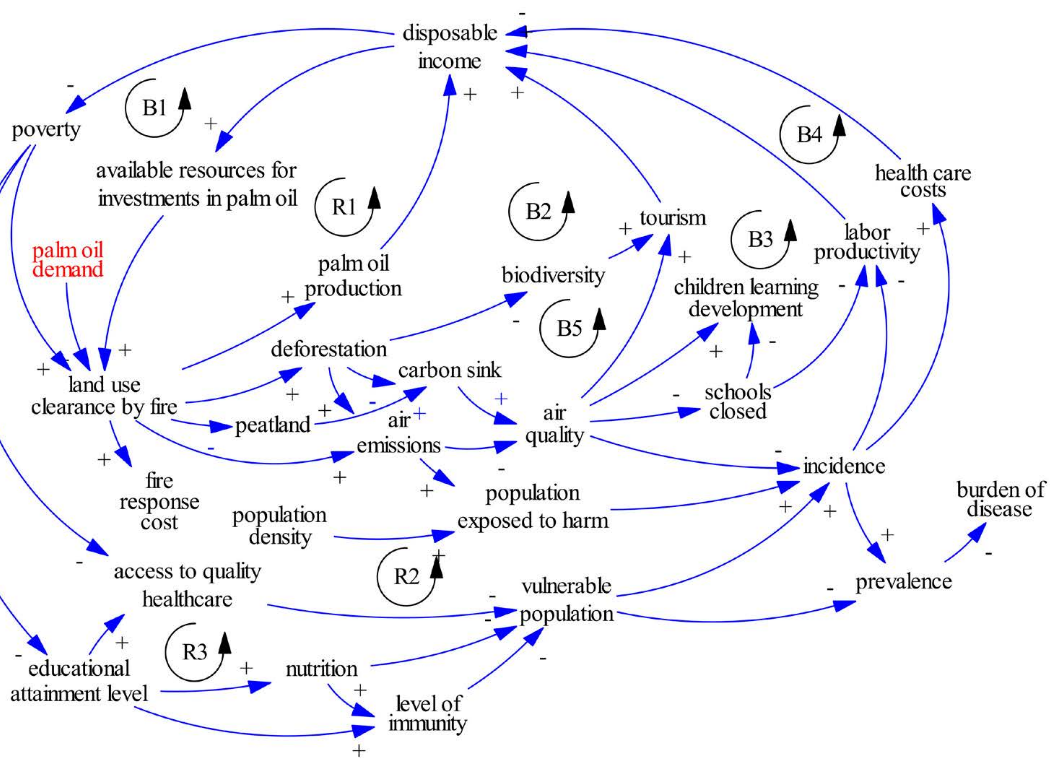
CLDs support the identification of relevant indicators in all four components presented in Fig. 5 as well as enable the identification of key interlinkages (and feedback loops) emerging from the framework presented in Fig. 3.

As described by John Sterman: "*A causal diagram consists of variables connected by arrows denoting the causal influences among the variables. The important feedback loops are also identified in the diagram. Variables are related by causal links, shown by arrows. Link polarities describe the structure of the system. They do not describe the behavior of the variables. That is, they describe what would happen if there were a change. They do not describe what actually happens. Rather, it tells you what would happen if* *the variable were to change" (140)*. Practically, the creation of a CLD supports (i) the selection of relevant indicators; (ii) the determination of causality among these variables; and (iii) the identification of critical drivers of change (e.g. feedback loops, or circular relations) that are primarily responsible for the past, present and future behaviour (or trends) of the system.

The use of CLDs is proposed because (i) CLDs elicit knowledge and create a shared understanding of the key drivers of change of a system, and hence on the possible outcomes of policy implementation across sectors and actors (i.e. the many outcomes of various climate mitigation actions); (ii) CLDs highlight the boundaries of the analysis, supporting the inclusion of social, economic and environmental indicators in a single framework of analysis to fully capture the benefits of low carbon development; (iii) by visualizing how the variables in the system are interconnected, CLDs allow all project team members to reach a basic-to-advanced knowledge of the systemic properties of the issues analysed.

Once the diagram is complete, feedback loops are identified. "Feedback is a process whereby an initial cause ripples through a chain of causation ultimately to re-affect itself"*(141)*. Feedback loops are responsible for the behaviour of the system, and often, even if several loops are found, only two or three dominate the system in terms of strength. Specifically, feedback loops can be classified as positive or negative. Positive (or reinforcing) feedback loops amplify change and are typically identified by a 'R' notation, while negative (or balancing) counter and reduce change are identified by a 'B' notation. As a result, when the system shows exponential growth, the dominant feedback loops is reinforcing. When a diminishing trend or constant state of the system are observed, a balancing loop is dominant. Naturally, loop dominance can change over time, generating S-shaped trends (growth and then adjustment, or equilibrium) for instance.

Fig. 6. Causal loop diagram (CLD) representing the dynamics of land use clearance by fire and related direct, indirect and induced social, economic and environmental outcomes *(85)*



Legend:

- *A causal link from variable A to variable B is positive if a change in A produces a change in B in the same direction; a causal link from variable A to variable B is negative if a change in A produces a change in B in the opposite direction. Example: the more demand, the more production (plus sign); the more production costs, the less profits (minus sign).*
- *Feedback loops, represented in the diagram with an R or B sign surrounded by a circular arrow, can be classified as positive or negative. Positive (or reinforcing) feedback loops amplify change and are typically identified by a 'R' notation, while negative (or balancing) counter and reduce change are identified by a 'B' notation. Example: the more demand, the more production, the more employment, the more disposable income and the more demand (reinforcing loop); the more resource consumption, the more waste generation, the more recycling and the less resource consumption (balancing loop)..*

3.5.2. Overview of methods

Various studies have summarized the key steps required to carry out a valid assessment of health co-benefits. These include work by Remais et al. (2014) *(137)*, Hess et al. (2020) *(138)* and Chang et al. (2017) *(142)*. The following recommendations are relevant for this report:

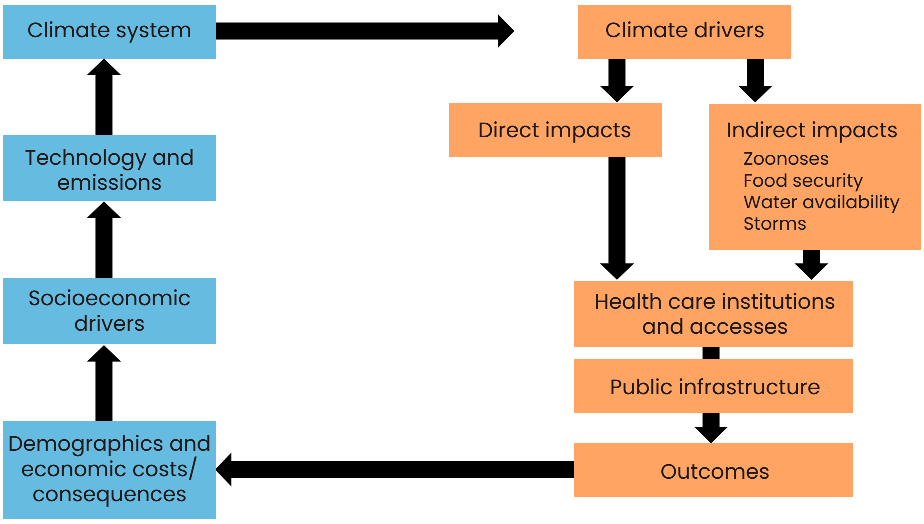
- Consultations with policy-makers and scientists from different disciplines are necessary to make sure that a large variety of potential impacts and co-benefits are considered;
- The period over which the health impacts are considered has to take into account the lifetime of investments (e.g. 60 years for built infrastructure) as well the climate impacts (e.g. both short term as well as up to 2100).
- Consider various climate scenarios in the analysis (RCPs and SSPs), and explore uncertainties explicitly, estimating the variability of results under different assumptions.
- Present the results in a format that can be used directly in policy processes, e.g. at the level of issue identification (cost of inaction), policy formulation and evaluation (e.g. CBA, CEA, multi-criteria analysis [MCA]).

A first factor to consider when reviewing methods and models is the scale of the analysis. Certain models focus on macroeconomic dynamics, treating the health sector as an economic sector. Other models project health expenditure at the individual level *(143)* and categorize health forecasting models as follows:

- Models that focus on individuals as the unit of analysis for their projection are called *microsimulation models*, which are useful to test relatively detailed "what if" scenarios arising from different policy options.
- *Sectoral models*, which include a vast variety of forecasting models that analyse performance at the sectoral level, e.g. energy, water, agriculture, both from a physical and economic perspective. Health outcomes emerge from sectoral trends.
- *Macro-level models* track aggregate economic performance and health expenditure at the national level. These models are used to assess the outcomes of national medical spending growth as well as to assess the implications of higher governmental health expenditures on economic growth.

Second, the thematic boundaries of models should be considered. The many and varied impacts of climate change call for the understanding of regional and local changes and how these shape the interaction among social, economic and environmental indicators *(3)*. Understanding the complex interactions across these dimensions of development requires the use of a systemic approach. Models that adopt ST include feedback loops, delays and non-linear dynamics *(139)*. Fig. 7 shows a simplified closed-loop system, where health drivers are impacted by health outcomes. Such models allow testing policy outcome, adaptation and institutional response to policy changes and external trends (e.g. global warming).

Fig. 7. Health outcomes from a systems thinking point of view (National Research Council, 2015)



Third, if the boundaries of the models identified are not broad enough, the use of multiple models should be considered. These models could be interconnected to one another using soft or hard coupling. Soft coupling implies that the results of a model are used as input for another model, but the two models run independently of one another. Hard coupling implies instead that the models are linked with equations (or code) and the models run in parallel or in sequence. Challenges emerge when performing model integration via hard coupling, where considerations have to be made about the treatment of time (e.g. whether models produce snapshots, run discrete events or semi-continuous simulations) and the method for solving equations (e.g. optimization, econometrics or extrapolation of trends, or simulation) *(144,145)*.

The availability of climate scenarios (RCPs and SSPs) from the IPCC has made it easier to use sectoral models and to perform soft coupling. These scenarios provide a common set of assumptions for different models, reducing the risk of using inconsistent assumptions across models. The use of these common underlying scenarios makes sense so that it is not a must to link the model used (sectoral or multisector and multidimensional), local or national, to a global climate model.

Fourth, the method for solving equations should be considered, regardless of the need to merge models. The use of optimization, extrapolation of trends, or simulation impacts the results of the analysis *(144,145)*. For instance, optimization models allow for a correction, or readjustment of decisions to adapt to the shock introduced. This results in the likely underestimation of short-term impacts, and of the severity of the shock. This is an important consideration to make when plans have to formulated for emergency response, as an example. Econometric models may tend instead to overestimate the impacts of inaction. This is because forecasts are created by extrapolating past trends, and if events of unprecedented nature or magnitude emerge, the forecasts would reach into uncharted territory for which there are no historical data to use as validation. A potential response of the local population or governments to a crisis may then be underestimated. Simulation models have different characteristics, and run "what if" scenarios. In this case, the model forecasts the likely outcomes of action or inaction in ways that should better reflect reality. On the other hand, these models cannot provide indications on what the best strategy or size of the investment would yield the best, or most desirable outcome. This is because these models do not optimize the system. Each method and model has strengths and weaknesses, and their use should be assessed based on the problem at hand. Understanding the way in which model equations are solved is critical for the selection of models, for a correct interpretation of a model's results and for informing decision-making.

3.5.3. Costing climate change impacts on health and health co-benefits

Several approaches are available to evaluate potential health impacts estimated with sectoral models, from non-monetary approaches such as the disability-adjusted life years (DALYs), quality-adjusted life years (QALYs) and healthy life years (HLYs), to monetary approaches such as the value of statistical life (VSL), value of life year lost (VYLY), and cost of illness *(146)*

Non-monetary methods can be less controversial compared to monetary approaches since the latter place a monetary value on human life *(146)*. However, monetary approaches can be used in CBAs, where the costs and benefits of various options are compared.

One of the most widely used non-monetary approaches is DALYs, which uses time as a standard metric, also considering both premature death and years lost due to health diseases or conditions *(146)*. DALY is calculated as the sum of the years lost due to disability (YLD) and the years lost due to premature death. Each DALY represents a year lost of "healthy" conditions.

Considering monetary approaches, the VSL can be defined as "the marginal rate of substitution between income – or wealth – and mortality risk *(147)*". This approach indicates the willingness to pay of single individuals to decrease mortality risks. VSL can be used in CBAs to assess the efficiency of policies designed to reduce those risks. On the other hand, care should be taken to avoid the use of unrealistic assumptions. For instance, the VSL is often calculated at the national level as an average across all population groups and income classes. On the other hand, in reality there can be population groups that express a different willingness (or ability) to pay. This differentiation should be considered explicitly, and to the extent possible, when adopting the VSL. Considering the prominence of mortality risk reductions as "justification" for policies, the VSL is usually part of the regulatory process in different countries including the United States *(148)* and has been studied mainly in reference to countries of the European Union, given its advantages when working with large population samples *(16)*. It is also worth noting that the VSL may be overestimated in the literature and incorrectly applied in policies *(147)*. The VSL is also related to the concept of VYLY. In other words, the same valuation approaches can be used to monetize the time (years) lost due to premature death *(148)*.

Cost of illness can be defined as the monetary value of the resources that are spent or lost as a consequence of a health-related problem *(149)*. It includes the value of lost/decreased productivity and direct health costs such as hospitalization and medication. Besides, it usually also considers the costs of the families of patients, since non-refunded costs may arise, such as transportation to visit the patient and costs for taking care of a person undergoing treatment. Families are also affected by decreased and lost productivity.

In addition to the health-related cost, "action-based" models include the cost of implementing policies for prevention in the health sector as well as climate action resulting in the creation of health co-benefits. Section 6.2 will discuss more in detail, but to give a general idea, Boxes 5 and 6 show real-life examples from different domains.

Box 5. A real-life example of estimating the costs and benefits of climate mitigation: active transport in Austrian cities

A study of the costs and benefits of climate mitigation in the transportation sector in three Austrian cities *(150)* uses the following steps to perform an economic valuation:

- Mitigation measures considered include switching from driving to public transport and active mobility such as walking and cycling. The study includes three scenarios: (i) green mobility: politically accepted modal share targets; (ii) green exercise: going beyond the politically accepted targets; and (iii) zero emission: the green exercise scenario with electric vehicles.
- A Transport Modelling Tool uses the approved modal share targets in the three cities to model changes in emissions from changes in transport mode scenarios. Next, the network emission model (NEMO) uses these data to estimate road transport emissions. Finally, a Lagrangian Dispersion Model uses these data to model changes in emissions and pollutant levels.
- All investment and operating costs of the proposed mitigation measures throughout the project period are calculated using the Austrian statistical classification of economic activity (ÖNACE)[e] and separated into public or private expenditures;
- Private expenditures related to shifting to walking or cycling are calculated based on data from the Austrian Household Budget Survey;
- Household mobility spending is combined with transport performance data to arrive at cost per saved car-kilometre;
- A cost-of-illness approach is used to analyse direct (medical procedures and services including patient transportation and accommodation) and indirect (productivity losses from morbidity and mortality) costs (data to validate household expenditures such as travel and accommodation of patients' relatives could not be obtained), as well as intangible costs (the cost of pain and suffering and the value of life lost);
- While Wolkinger et al. (2018) *(150)* use both value of a life year (VOLY) and VSL metrics, they suggest the former may be more useful in the context of air pollution which has an incremental negative impact on life expectancy. VOLY is used to value changes in life expectancy while VSL is suitable for valuing the effects of mortality *(17);* therefore, variation is expected when using both methods.
- The "health model" projects changes in mortality from cardiovascular, respiratory and other relevant diseases, expressed as deaths as well as YLD or years of life lost due to premature mortality (YLL).

These results are processed using the "economic assessment tool" which modelled macro- and microeconomic costs (changes in public and household costs from switching from cars to other modes of transport, as well as related changes in direct and indirect health costs for different scenarios).

The study shows that proposed measures result in reduced vehicle mileage, energy use, and in GHG emission reductions of about 290 000 tonne CO_2 equivalent in the green mobility scenario, 530 000 tonne CO_2 equivalent in the green exercise scenario, and 1 000 000 tonne in the zero emission scenario (due to a switch to electric engines) relative to BaU. The study projects avoided deaths from lack of physical activity and NOx exposure, of up to 76 per 100 000 population in the most ambitious zero emission scenario. The study demonstrates how capturing intangible costs, the co-benefits of sustainable transport can offset the projected losses in employment and GDP. The authors estimate that savings would range from €3 to 5.5 million per year at an average cost factor of €1.7 per 1000 passenger km, or from €5 to 55 million, depending on the scenario, not including the effects of reducing noise and congestion that were not valued *(150)*.

[e] Unternehmensservice Portal. (2021). ÖNACE. https://www.usp.gv.at/lexikon/oenace.html.

Box 6. An example of modelling dietary changes as a result of pricing food-related GHG emissions in different regions of the world *(135)*

Pricing food-related emissions may result in increased food prices, which may have consequences for food security. The study uses life-cycle analysis data to quantify food-related emissions and put a price on food commodities based on their emission footprint, by region and food group, for the year 2020.

The analysis has five steps:

- Estimating the impact of GHG taxes on all food commodities;
- Exempting health-critical food groups from taxation;
- Creating scenarios for animal-based foods, red meat and beef;
- Adding a compensation for income losses due to GHG taxation;
- Adding a subsidy for fruit and vegetable from GHG tax revenues.

The IMPACT global agricultural model is used to forecast consumption of agricultural commodities. IMPACT is based on a partial equilibrium multi-model encompassing agricultural supply and demand. The study includes main scenarios and sensitivity analysis. The main analysis focuses on mortality. The sensitivity analysis considers premature deaths, YLL and DALYs.

The health co-benefits are estimated based on dietary risk factors and weight risk factors. The study suggests that the health benefits from reducing obesity rates through dietary choices could outweigh the health losses from increased underweight in most of the world, except some low-income countries.

An estimated reduction in mortality is 100 000–500 000 globally. An environmental co-benefit of reduced consumption of beef and dairy is estimated at 1 $GtCO_2$ equivalent.

While this particular study *(135)* does not provide an economic valuation of the outcomes, in an earlier study, Springmann et al. (2016) *(151)* suggested that a global switch to a plant-based diet could result in economic benefits of up to US$ 31 trillion (up to 13% of global GDP in 2050), in addition to reducing mortality by up to 10% and food-related GHG emissions by 70%, compared to a reference scenario.

3.5.4. Literature review of models

As introduced above, several methods and models are available for the estimation of health impacts and their economic valuation. Table 4 and Table 5 provide several examples, albeit not being exhaustive, for models that support the estimation of health co-benefits of climate mitigation and adaptation and for performing their economic valuation.

Several types of models are presented, organized by thematic area (e.g. climate mitigation in the energy sector or agriculture). The goal is to provide relevant information on available models to researchers and policy analysts who work in such thematic areas, not to point to specific models. Further, some of the models listed are cross-sectoral and multidimensional and can hence generate results that may be of use to several audiences.

A few examples of models and their applications are presented in more detail next. This is to add more depth to the list of models presented in Table 4 and Table 5, while acknowledging that papers, reports and full modes documentations are also available.

Sectoral – energy (mitigation)

As shown in a recent study exploring the impacts of renewable energy projects on air pollutant emissions in the US electrical grid *(4)* environmental policy modelling generally includes a number of interconnected models and valuation techniques. The environmental policy simulation tool for electrical grid interventions v2.0 (EPSTEIN 2.0) used in the study consists of three tools:

- The avoided emissions and generation tool (AVERT) from the US Environmental Protection Agency (EPA) using historical power generation and emissions data to predict electrical demand for each power plant, helping estimate renewable energy deployment and energy efficiency benefits;
- Social cost of carbon (SCC) to calculate the marginal cost of an extra tonne of CO_2, including some health costs, and to value benefits of CO_2 emission reductions; and
- Estimating air pollution social impacts using regression (EASIUR) to assess health benefits.

Economywide – energy (mitigation)

Another modelling study illustrates the use of an integrated model combining air quality, health and economic valuation tools in line with different SSPs and mitigation scenarios to estimate health co-benefits of climate change mitigation *(14)*. The Asia-Pacific integrated assessment/computable general equilibrium (AIM/CGE) model includes the following models *(14)*:

- community multiscale air quality (CMAQ) to model PM2.5 and O_3 levels (here BC, NMVOC, NOx and SO_2), linked to a health impact assessment model;
- Integrated model of energy, environment and economy for sustainable development/computable general equilibrium (IMED/CGE) for economic valuation of these health impacts in South Korea.

Developed by Peking University, IMED/CGE has been used to model the economic costs of mitigation in different regions of China; here, it compares carbon prices from multiple Integrated assessment models (IAMs) to model mitigation costs. Given that AIM/CGE does not represent Korea separately from the rest of the Asia-Pacific, IMED/CGE is used for this purpose.

Spatially explicit – air pollution

A study of the health impacts of black carbon (BC) ambient concentrations in the United States *(18)* illustrates the use of the open-source Environmental Benefits Mapping and Analysis Program (BenMAP), which is a user-friendly modelling software incorporating tools and country datasets to allow for full-scale assessments. The study uses BenMAP to build a log-linear health impact function based on:

- air quality modelling (average BC concentrations across the United States are modelled using the GEOS–chem atmospheric chemistry model);
- affected population, baseline indices of morbidity and mortality and modelled morbidity and mortality (a concentration–response coefficient [β] is calculated to model BC health impacts) complete the assessment.

City level – energy (mitigation)

A modelling study of the impacts of climate policies at the city level *(152)* updates the GAINs model originally developed by the International Institute for Applied Systems Analysis (IIASA) to analyse co-benefits of climate policies globally and nationally. In this study the model is updated to ensure that it can assess not only sectoral impacts on emission reductions but also the impacts of individual policies at the city scale. The update included adjustments reflecting China's emissions data and emission source categories. The resulting GAINs-City model is used to forecast the effects of policies related to power plants, industrial processes, transportation and other sectors. Among other things, the GAINs-City models a new standard for vehicle fuel emissions, reallocating fuel between vehicles complying with different standards *(152)*. Notably, the study shows that rates of emission reduction depend on policy execution time and policy stringency; e.g. advancing the implementation of China's VI heavy duty diesel fuel standard by four years is modelled to increase emission reduction 2.3 times by 2030. This study is an example of how regional climate models (RCMs) dynamically downscale outputs of the global climate model (GCM) to help model regional and local climate processes *(49)*.

Table 4. Overview of simulation models available for the analysis of health co-benefits of climate mitigation

Sector	Method/framework	Model	Inputs	Health indicators	Reference
Mitigation					
Energy	Electrical grid model. Simulation, static	EPSTEIN 2.0, made of the avoided emissions and generation tool (AVERT) and estimating air pollution social impacts using regression (EASIUR)	Reductions in air pollutant emissions from power plants	Air pollutants, concentration, mortality and morbidity impacts	*(153)*
	Energy demand and power generation model. Simulation, system dynamics	Global subsidy initiative – integrated fiscal (GSI-IF) model	GDP, energy prices, fossil fuel subsidy removal and carbon pricing, renewable energy and energy efficiency targets	Energy use by sector and source; air pollutants from direct energy use and power generation	*(154,155)*
	Coupled models, including CGE, air quality and concentration–response functions. Optimization	Asia-Pacific integrated assessment/computable general equilibrium (AIM/CGE), community multiscale air quality (CMAQ) modelling system; health assessment (concentration–response function), and economic models (Integrated model of energy, environment and economy for sustainable development/computable general equilibrium (IMED/CGE)	Emissions and air pollutant forecasts, health impacts of PM2.5 and ozone (O_3) concentrations, carbon price	Air pollution – mortality and morbidity impacts	*(14)*
		Global exposure mortality model (GEMM)	PM2.5 and O_3 emissions (based on the global burden of disease methodology)	Air pollution – mortality and morbidity impacts	*(26)*
		Simplified GHG policy assessment model (GHG-PAM)	PM and carbon emissions	Air pollution – mortality and morbidity impacts	*(66)*
		CaRBonH	Scenario of air pollutant emissions	Air pollution – mortality and morbidity impacts	*(156)*

Sector	Method/framework	Model	Inputs	Health indicators	Reference
Mitigation					
Energy	Energy forecasting models, with estimation of air pollutants. Optimization	LEAP-IBC, long-range energy alternative planning (LEAP) – Integrated Benefits Calculator (IBC)	Demand for energy services, energy balance	Air pollutants from direct energy use and power generation	*(157)*
		Energy and Clean Air (Creahia)	Air pollutants emissions from power plants	Air pollution – mortality and morbidity impacts	*(158)*
		TM5-fast scenario screening tool (TM5-FASST)	Change in energy demand	Air pollution – mortality and morbidity impacts	
		Global change analysis model (GCAM)	Emission factor for each technology and every pollutant	Air pollution – mortality and morbidity impacts	*(9)*
		Greenhouse gas and air pollution interactions and synergies (GAINS)	Estimations of the potential emission reductions from around 2000 emission control measures	Air pollution – mortality and morbidity impacts	*(159)*
		Regional model of investments and development (REMIND)	Forecasts the evolution of the energy sector with a special focus on impacts of air pollution	Air pollution – mortality and morbidity impacts	*(160)*
		MERLIN	Air pollution control measures	Air pollution – mortality and morbidity impacts	*(161)*
Waste	Material flow model, with resulting emissions	Green economy model (GEM)	Quantity of waste generated, waste management flows	GHG emissions and other pollutants, cost of waste management	*(162,163)*
Agriculture and livestock	Food production and supply available to consumers	Country-level microsimulation model of zinc and iron deficiency to project the health effects of zinc- and iron-deficiency-related diseases in terms of disability-adjusted life years (DALYs) accumulated over the period 2015 to 2050, worldwide	Climate change impacts, crop nutrient concentrations, dietary patterns and disease risk	Indirect human-mediated health impacts (e.g. nutritional deficiencies) – malnutrition and undernutrition, number of people affected	*(164)*

Sector	Method/framework	Model	Inputs	Health indicators	Reference
Mitigation					
Agriculture and livestock		Model for estimating future undernutrition	Climate change impacts, crop nutrient concentrations, dietary patterns and disease risk	Indirect human-mediated health impacts (e.g. nutritional deficiencies) – malnutrition and undernutrition, number of people affected	*(75)*
		International model for policy analysis of agricultural commodities and trade (IMPACT)	Food affordability, food availability, nutrient adequacy and dietary diversity	Malnutrition and undernutrition, number of people affected	*(135,165)*
		Food estimation and export for diet and malnutrition evaluation (FEEDME)	Mean calories on a per capita basis and food access	Malnutrition and undernutrition, number of people affected	*(166)*
Land use, land-use change and forestry (LULUCF)	Climate models that forecast changes in heat stress and vector-borne diseases based on land cover and population density	MaxLike, Climate envelope, Maxent, Biomod2 ensemble model, GARP, LOBAG-OC	Climate, spatial, and socioeconomic factors (such as vulnerability)	Parasitic and vector-borne diseases – number of people affected	*(167)*
		Five malaria models: LMM_RO, MIASMA, VECTRI, UMEA, and MARA driven by climate outputs from global climate models (GCMs)	Climate, spatial and population scenarios on malaria transmission	Parasitic and vector-borne diseases – number of people affected	*(168)*
		Global climate models (GCMs)	Heat stress indicators based on both temperature and humidity condition	Health impacts from extreme weather events: heat-related illness/ deaths	*(169)*
		The community climate system model version 3 (CCSM3) (system composed by a group of coupled models capable of carrying out earth's climate system by simulating its atmosphere, ocean, land surface and sea-ice)	Climatic and spatial factors	Health impacts from extreme weather events: heat-related illness/ deaths	*(170)*

Sector	Method/framework	Model	Inputs	Health indicators	Reference
Mitigation					
Industrial processes and product use (IPPU)	Models forecasting the outcomes of IPPU emissions, e.g. on ozone and PM2.5	Two climate models (the community earth system model, CESM and causal masked multimodal model, CM3) and two air pollutant emission scenarios (using the community multiscale air quality or CMAQ)	Projected changes in climate and concentrations of O_3 and particulate matter (PM2.5)	Air pollution – mortality and morbidity impacts	*(171)*
		Excel toolbox developed by the EU-funded INTARESE project	Projected changes in stratospheric ozone associated with decreasing emission of O_3-depleting substances and increasing emissions of CH_4 and N_2O	Air pollution – mortality and morbidity impacts	*(172)*
		Combination of an energy projection model (LEAP) an emission estimation model, an air quality simulation model (CMAQ), and a health benefit evaluation model (BenMAP), to assess the co-benefits of two different sets of energy policies	Industry energy savings	Air pollution – mortality and morbidity impacts	*(173)*

Table 5. Overview of simulation models available for the analysis of health co-benefits of climate adaptation

Sector		Method / Framework	Model	Inputs	Health indicators	Reference
Adaptation						
Land	**Agriculture**	Systems thinking		Data sources may be both direct (e.g. daily count of emergency calls and responses to climate-related disasters) and indirect (e.g. insurance industry data)	Health impacts from extreme weather events and natural disasters; food and water insecurity, malnutrition and undernutrition, disabilities, child stunting, displacement of people	*(174)*
	Forestry	Simulation	GEOS-Chem chemical transport model	Fire emissions records, smoke exposure during haze events, emissions sources, health impacts	Health impacts from extreme weather events and natural disasters: population-weighted smoke exposure	*(175)*
Health		Optimization and simulation	Brace framework	Climate-induced identification of direct and indirect exposures and associated health impacts	Identification of the best available science to project likely climate change health impacts in a given jurisdiction and prioritize interventions	*(176)*
			HIA framework	Health risks connected to climate change (depending on the study)	Health impacts connected to climate change (depending on the study)	*(153)*
						(177)
						(178)
						(179)

Sector	Method / Framework	Model	Inputs	Health indicators	Reference
Adaptation					
Water	Optimization and simulation	InVEST – urban flood risk mitigation	Data sources include precipitation within a watershed, as well as the capability of permeable green areas to reduce runoff	Identification of vulnerable areas from extreme rainfall events	*(180)*
		Hydrologic Engineering Center–hydrologic modelling system (HEC–HMS)	The inputs include a combination of remote-sensing outputs and the calculation of weighted curve numbers	Effects of land-use change on flood risk	*(181)*
		Soil and water assessment tool (SWAT)	Digital elevation model (DEM), soil data, land use data, stream network layers, weather and climate data (rainfall and temperature) and stream discharge data	Impacts of land management on flood hazard	*(182)*
Infrastructure		Dynamic interactive vulnerability assessment model (DIVA)	Impacts of upgrading flood-protection infrastructures	Health impacts from extreme weather events and natural disasters: floods	*(153)*
	System dynamics and project finance	SAVi – sustainable asset valuation	Specifics of the infrastructure assessment (size of the project, timing, lifetime)	Depending on the asset, air and water pollution, heat stress, health costs under different climate scenarios	https://www.iisd.org/savi/

4 How to prioritize interventions based on CBA and CEA

Economic assessments of climate action often fail to include associated health co-benefits, even though, as an example, mitigation policies and technologies can modify health-related risks and exposures such as air pollutants, diet and physical activity *(142)*. Excluding avoided costs emerging from health co-benefits can result in an unbalanced assessment of the economic viability and desirability of climate mitigation and adaptation actions.

The assessment of both costs and benefits, physical or monetary, is a critical step to inform decision-makers on how to prioritize resource allocation for climate action as well as for development *(183)*. This assessment should be guided by the goals of the climate actions envisaged. Options include:

- Reducing or completely avoiding the expected or observed impacts of climate change;
- Restoring the level of well-being to pre-climate change periods; and
- Continuing with the current level of risk, implementing adaptation measures to avoid an increase in the risk, or reducing risk in a cost–effective way.

On a practical level, goals can vary between countries, regions, societies and time context. Many options can be followed based on exposure to climate change impacts (in relation to climate impacts), potential to improve adaptive capacity (in relation to climate adaptation), as well as contribution to reduction in global GHG emissions (in relation to climate mitigation).

On the other hand, the goal set by decision-makers can guide the choice of the method used to evaluate the envisaged policy interventions and related investments. The most common methods available to assess investments include *(183)* cost-benefit analysis (CBA), or multi-criteria analysis (MCA) when using qualitative indicators in addition to quantitative ones, and cost-effectiveness analysis (CEA).

The main difference between CEA and CBA is that while the CEA provides a comparison of cost and outcome, CBA instead provides a comparison of cost and the economic value of the outcome. Practically, the CEA calculates the cost required to avoid a given undesirable health outcome (e.g. cost per heat-related stroke avoided); on the other hand, the CBA compares the investment required with the economic benefit such investment would realize. This difference implies that, in principle, CEA may suggest to make investments that are not necessarily economically viable, but are more effective than others; CBA may suggest to make investments in areas that are most economically viable, but not necessarily relevant in relation to the challenge at hand.

It is implicit in the CEA that the economic viability of the investment is of secondary importance, i.e. if a problem has to be solved it will be solved in the most efficient way possible, even if the investment will not be paid back. On the other hand, it is implicit in the CBA that the option with the highest benefit-to-cost ratio (BCR) is the most desirable investment and the only one worth acting upon.

CBAs can be complemented by MCAs, which include qualitative indicators in the analysis. In MCA, qualitative indicators, those of relevance to the investment but cannot be quantified with confidence, are assigned a rating, weights are assigned to each indicator and a synthetic score is calculated. When indicators of relevance and urgency of the problem to be solved are included in the analysis, MCA merges the advantages of CBA and CEA in a single assessment.

It emerges from the above that both CBA (with the possibility to extend the analysis to an MCA) and CEA are useful tools to prioritize options for policy interventions. The use of one method does not exclude the other. On the contrary, CBA and CEA are complementary methods. In the context of this study, both CBA and CEA use the same input information. Practically, Assessment 1 presented in Fig. 3 highlights the need to first estimate the burden of disease or health impact and related cost in the case of inaction. The number of cases is necessary for a CEA, while the cost of inaction is essential for a CBA. Thus, the framework presented in this report supports the creation of both CBA and CEA.

4.1. Cost–benefit analysis (CBA)

The analysis proposed in this report is systemic and comprehensive. As a result, the CBA has to be comprehensive also, and capture all relevant direct, indirect and induced outcomes of policy implementation, from an economic perspective.

The CBA requires to assess the outcomes of policies and investments using three main components, namely investments, avoided costs and added benefits, taking into account both social and environmental avoided costs and added benefits in addition to the more traditional economic ones, including health co-benefits. This is necessary to link climate mitigation and adaptation outcomes on health to microeconomic and macroeconomic performance.

An example of relevance is fuel switching from fossil fuels to renewable energy, which reduces the use of hazardous fossil fuels, energy costs and emissions, in addition to reducing air pollution and having positive climate impact, and resulting in the related impacts on the burden of disease and health costs.

- **Investments**: From a private sector perspective, investments refer to the monetary costs of implementing a decision. For renewable energy operators, increased investment in the sector entails, among others, the cost of solar panels and wind turbines in the context of power generation, implementation and maintenance. From a public sector point of view, investments refer to the allocation and/or reallocation of financial resources with the aim of reaching a stated policy target such as creating enabling conditions for investment. For this example, it may include public expenditure for incentives for renewable energy, or the cost of providing preferential loans, or collateral. In the case of public procurement, the investment would be related to the actual capacity of the renewable energy system (MW, installation and operation and maintenance costs).
- **Avoided costs**: The estimation of potential avoided costs considers the results of the successful implementation of an investment or policy. In the case of switching to renewable energy, these avoided costs refer to direct savings derived from reduced fossil fuel energy purchases, or the overall cost reduction for power generation and transmission lines when using renewables that are either centralized or decentralized. Importantly, other avoided costs include health costs that would decline as a result of reduced emissions and air pollution. These can be measured in the form of premature deaths avoided and life value savings, or savings in public health budgets.
- **Added benefits**: Among the added benefits are the monetary value of economic, social and environmental outcomes deriving from investment or policy implementation, beyond the performance of the baseline scenario, focusing on short-, medium- and long-term impacts across sectors and actors. This includes health benefits in terms of labour productivity (not seen as an avoided cost, but as an increase of productivity beyond baseline values), as well as increased employment (with renewable energy being more labour-intensive than other centralized thermal power generation). For some specific contexts, added benefits emerge also from the increased economic competitiveness resulting from lower costs and prices of electricity generation, or from the higher reliability of electricity generated from renewable energy, leading to higher GDP and public revenues. These are all additional benefits that would not accrue in a BAU scenario.

As indicated above, in this specific example, an integrated CBA would include investments in renewable energy capacity and operation and maintenance. Avoided costs include reduced use of fossil fuel, avoided costs (construction and maintenance) of thermal power generation capacity and possibly avoided subsidies on fossil fuel (either directly allocated to fossil fuel production, consumption or to electricity consumers). Avoided health costs, public and private, avoided cost of emissions (e.g. contribution of air emission to global climate change impacts, e.g. SCC) are also considered. In relation to added benefits, (i) net employment and income creation, if in addition to the baseline scenario, (ii) higher GDP due to a more productive labour force and/or to the creation of new value chains should also be considered along with actor-specific macroeconomic impacts (e.g. higher GDP for firms translates into higher public revenues for the government, and higher consumption for households). Tables 6–9 provide examples of such CBAs.

This type of analysis allows one to determine whether a given policy or investment is economically viable for the intent it was created, as well as if it is economically viable from a societal perspective, taking into account all potential synergies and trade-offs.

Table 6. CBA energy

Energy: Renewable portfolio standards (RPS)	
CBA	**Based on Mai et al. (2016) *(184)*, on Wuennenberg et al. (2021) *(185)*, and on sections 2 and 3**
Costs	
Capital cost of renewable energy technologies (e.g. solar panels, wind turbines)	
Operations and maintenance cost of renewable energy technologies	
Avoided costs (health-related)	

Air pollution reduction:
• Morbidity
  • Cost of illness
    – Avoided/reduced treatment costs from reduced use of fossil fuels (respiratory diseases, cardiovascular damage, cancer, fatigue, headaches and anxiety, irritation of the eyes, nose and throat, damage to reproductive organs, nervous system damage)
    – Work absence and productivity (income loss)
• Mortality
  • Value of statistical life (VSL)
  • Value of life year lost (VLYL)	

Added benefits	
Job creation and related income generation	
Increased economic competitiveness	

Table 7. CBA waste

Waste: Municipal waste management	
CBA	**Based on McGoodwin (2018)** ***(186),*** **and on sections 2 and 3**
Costs	
Capital costs	
Operations and maintenance costs	
Avoided costs (health-related)	

Reduced air, soil and water pollution
• Morbidity
  • Cost of illness
    – Avoided/reduced treatment costs of cancer, lymphoma, malformations, mortality; impacts on reproductive organs, well-being, as well as impacts of vector- and waterborne, and zoonotic diseases
    – Work absence and productivity (income loss)
• Mortality
  • Value of statistical life (VSL)
  • Value of life year lost VLYL)	

Avoided emissions due to energy recovery (social cost of carbon [SCC])	
Added benefits	
Revenues from electricity sold	
Revenues from compost sold	
Revenues from recyclables	

Table 8. CBA Infrastructure

<table>
<tr><th colspan="2">Infrastructure: Buildings</th></tr>
<tr><th>CBA</th><td rowspan="13">Based on Bassi et al. (2021) (187), and on sections 2 and 3</td></tr>
<tr><th>Costs</th></tr>
<tr><td>Capital costs</td></tr>
<tr><td>Operations and maintenance costs</td></tr>
<tr><th>Avoided costs (health-related)</th></tr>
<tr><td>Reduced impact of infrastructure damage (avoided impacts from overheating, flood damage, indoor air pollution, extremes of temperature and biological contamination)
• Morbidity
  • Cost of illness
    – Avoided/reduced treatment costs of exhaustion, cramps, syncope, strokes, kidney disorders, psychiatric illness, chronic pulmonary illness, diabetes, cerebrovascular accident, vector- and waterborne diseases, drowning, injuries, hypothermia, wounds, poisoning, affected mental health, communicable diseases, starvation, forced migration, impacts on well-being
    – Work absence and productivity (income loss)
• Mortality
  • Value of statistical life (VSL)
  • Value of life year lost (VLYL)</td></tr>
<tr><th>Added benefits</th></tr>
<tr><td>Job creation and income</td></tr>
<tr><td>Increased property value</td></tr>
<tr><td>Ecosystem services (such as carbon storage, flood retention, habitat quality)</td></tr>
<tr><td>Improved quality of service provided (e.g. for health facility)</td></tr>
<tr><td>Improved volume of service provided (e.g. for health facility)</td></tr>
</table>

Table 9. CBA land

<table>
<tr><th colspan="2">Land: climate-smart agriculture</th></tr>
<tr><th>CBA: Adapted crops</th><td rowspan="12">**Based on Ng'ang'a et al. (2017) *(188)*, and on sections 2 and 3**</td></tr>
<tr><th>Costs</th></tr>
<tr><td>Capital cost</td></tr>
<tr><td>Operations and maintenance cost</td></tr>
<tr><td>Cost of seeds</td></tr>
<tr><th>Avoided costs (health-related)</th></tr>
<tr><td>Reduced impact of air, soil and water pollution
• Morbidity
    • Cost of illness
        – Avoided/reduced treatment costs of respiratory, dermatological, and neoplastic hazards. Reduced impacts of malnutrition.
        – Work absence and productivity (income loss)
• Mortality
    • Value of statistical life (VSL)
    • Value of life year lost (VLYL)</td></tr>
<tr><th>Added benefits</th></tr>
<tr><td>Production and revenues (farmers)</td></tr>
<tr><td>Income (individuals) and public revenues (government)</td></tr>
<tr><td>Improved labour productivity, from improved nutrition</td></tr>
</table>

While it may seem intuitive to consider all possible policy outcomes in a CBA, there are several barriers to consider for the quantification of such outcomes. According to Perkins et al. (2015) *(189)*, CBAs of large-scale interventions present challenges because of multiple actors incurring different costs; the benefits also can be hard to quantify due to the multiple causal pathways that exist within complex systems, and even attributing effects to large-scale interventions can be difficult. On the level of methodology, both revealed preference and stated preference techniques used for the CBA may present challenges: the former is not as effective for valuing public health interventions due to public goods being non-excludable and thus hard to valuate accurately, while the latter implies creating hypothetical scenarios, means of payment, the time period and level of risk associated with the intervention in question – all of which, coupled with valuating public goods delivered within large-scale interventions, may create valuation biases *(189)*.

Co-benefits and related cost reductions of low-carbon interventions are not often taken into account in decision-making processes because they are not easy to identify *(150)*. This process requires multi-stakeholder consultation/participation, which is often not common practice. Further, their quantification requires the use of several methods and models. For example, Wolkinger et al. (2018) *(150)* address this gap by analysing the co-benefits arising from improved air quality due to climate change mitigation policies in urban areas. To do so, the authors link a transport modelling tool with a transport emission model, an emission dispersion model, and a health model as well as a CGE macroeconomic model to analyse three mitigation scenarios. The results show that reduced exposure to air pollution leads to decreased morbidity and mortality. On the other hand, macroeconomic results, despite showing a strong positive welfare effect, also indicate slightly negative employment impacts and GDP. This type of work requires multidisciplinary knowledge, and collaboration across modellers. This is also a process that is not easy to implement. One of the reasons resides in the type of models used: for instance, different models use different methods for solving equations (e.g. optimization, extrapolation of trends and simulation) as well as different ways of treating time (e.g. generating results in the form of a snapshot, using discrete or semi-continuous time). These differences emphasize that linking models, via soft or hard linking, is not an easy task, or not even possible.

4.2. Cost–effectiveness analysis (CEA)

CEA is a method to analyse both costs and health outcomes of one or more interventions and determine which intervention is more appropriate (from the cost perspective) to a specific context. More specifically, it compares an intervention to another one by evaluating the costs to gain a unit of "health outcome" *(190)*.

CEA is a comparative approach; therefore, an intervention can be considered cost-effective only compared to another one. If the costs of realizing a health outcome with a specific intervention is lower than others (or than realizing a different health outcome), the results can be shown as absolute (e.g. US$ per case avoided) or as a cost–effectiveness ratio (e.g. 0.8 indicating a cost being 20% lower than another option).

To prioritize interventions, decision-makers should be able to compare the cost-effectiveness of policies and projects focused on climate change adaptation and/or mitigation and produce health benefits *(191)*. Ideally, the main goal of an intervention or policy of this type is to maximize the health benefits as well as the efficacy of climate actions (such as reducing GHG emissions), with the objective of the investment being given and not under question.

In this context, data availability and metrics are critical to estimate the cost-effectiveness of different interventions. It is critical to be aware of how costs can change over time (such as the costs of technologies) and how populations affected by climate change would evolve over time. However, there may not be sufficient data to capture all possible relevant factors, which would result in a partial assessment. Non-linear changes and effects also add complexity and uncertainty to the analysis. Assumptions are often used, in the context of scenario analysis, to capture those non-linearities. This is important to capture a full range of outcomes and reduce uncertainty in policy-making (e.g. the impact of climate change in the longer term may be more severe than current expectations).

4.3. Multi-criteria analysis (MCA)

MCA is used to assess complex issues that include choosing among multiple quantifiable and non-quantifiable criteria, such as in the case of energy system planning *(192)*. MCA can be an extension of CBA, adding qualitative dimensions to the more quantitative cost and benefit assessment. In this respect, an MCA can serve as a bridge between CBA and CEA, considering that there are other factors to consider beyond the economic viability of a policy or investment for determining the course of action to take in order to address health concerns.

To optimize and rationalize decisions, maximizing benefits and minimizing costs, MCA entails evaluating multiple attributes of policy or intervention outcomes, assigning utility values to them, and combining these assignments to arrive at an overall utility score *(192)*. Therefore, MCA aggregates various criteria to arrive at a single score for a given course of action. The chosen criteria may reflect different perspectives or needs, which makes MCA a subjective assessment method *(193)*.

In their study, Ekholm et al. (2014) *(194)* use MCA to assess relative benefits of heating oil substitutes and the associated trade-offs for three types of impacts: health, climate and acidification. The process included creating a single indicator from a weighted sum of the three impact types. Two weightings were used, based on (i) the policy goal of reducing air pollutant emissions; and (ii) CBA of the externalities in each impact category *(194)*.

MCA can be used with other methods such as life-cycle assessment for a more comprehensive analysis. Hermann et al. (2007) *(193)* weight their chosen criteria based on three perspectives: national, regional and local to assess the consequences of air pollution. From a global perspective, the impact categories move from global warming to health, in the order of importance, whereas from a local perspective they move in the opposite direction, illustrating the greater importance placed on health from a local perspective, compared to environmental impacts *(193)*.

5 Pilot-testing the framework to identify and quantify health gains from mitigation and adaptation actions

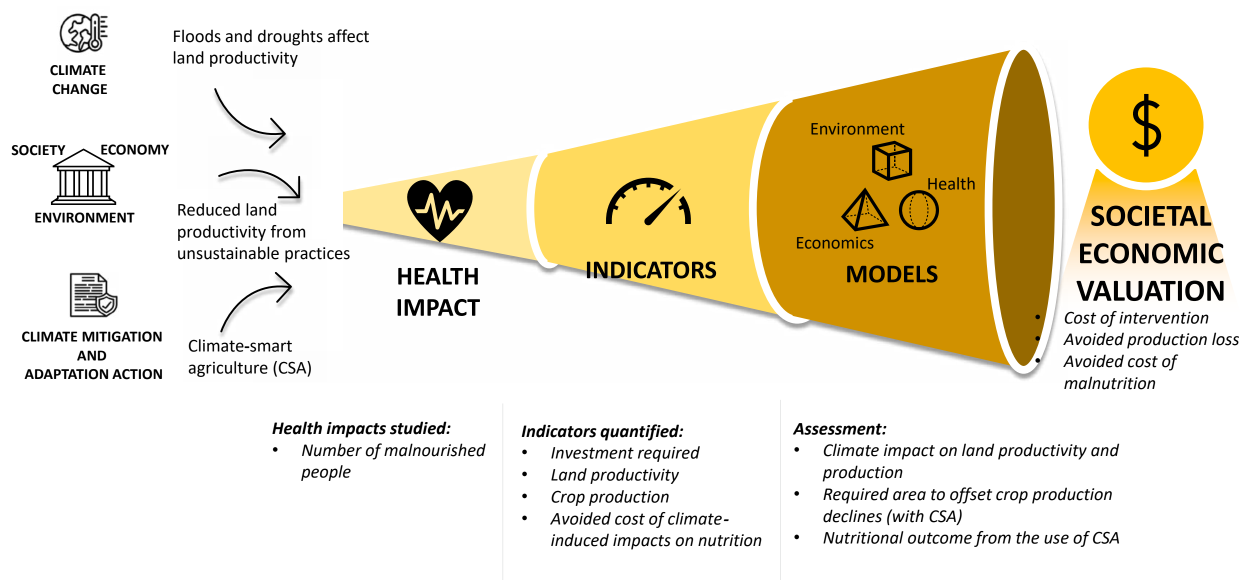
We pilot-tested the framework by working on the case study of Pakistan, considering selected examples of climate adaptation and mitigation options. The adaptation actions analysed include (i) CSA practices, (ii) planting trees to reduce heat and reduce the risk of floods, and (iii) improved building design. The mitigation options analysed include (iv) energy efficiency, (v) renewable energy for power generation and (vi) fuel switching. A sixth intervention option is presented that merges climate adaptation and mitigation goals: (vi) climate proofing of health facilities, with interventions that improve energy efficiency and increase energy self-sufficiency.

The sixth assessment also offers a different view on the relevance of the climate adaptation and mitigation sector for the health sector: the first five actions aim at reducing the impact of climate change on health (these are preventive measures), the latter instead aims at ensuring a smooth delivery of health services, regardless of the demand for health care. This highlights the wide variety of co-benefits that climate mitigation and adaptation action can generate for health and the health sector.

The following sections provide an overview of the intervention option, the rationale for action and means of intervention, as well as the health co-benefits estimated. The five steps to apply this framework, as described in chapter 3 and its subchapters, are applied to each of the options evaluated. Each of the following chapters begins with a summary of how the model is applied, considering Fig. 3, and then the different intervention options are analysed. Annex 2 provides additional details on the methods and model used to quantify health co-benefits.

5.1. Adaptation Action 1: Climate-smart agriculture

Fig. 8. Customization of the conceptual framework to climate-smart agriculture



Step 1 **Development impact on health**: the use of unsustainable production practices has led to an increase in soil erosion and reduced land productivity.

Step 2 **Climate change impact on health**: climate variability has resulted in an increased risk of droughts and floods, both impacting negatively on land productivity.

Step 3 **Climate action considered**: CSA practices, aimed at increasing land productivity by increasing resilience to climate change and supporting the implementation of sustainable practices, such as the use of integrated pest management rather than herbicides.

Step 4 **Indicators quantified**: investment required, impact on land productivity and production, avoided cost of climate-induced impacts on nutrition.

Step 5 **Models utilized**: data on land use productivity under normal conditions, climate change and climate-smart practices.

5.1.1. Overview

Climate change is affecting Pakistan's weather patterns. The country has seen a 0.76 °C temperature rise on average and droughts have become more frequent over the past years *(195,196)*. In the future, droughts are predicted to occur even more frequently. Droughts lead to reduced crop production for various reasons. First, from heat stress on plants; second, through an increased need for water through more evapotranspiration (evaporation from soil and transpiration from plants); and third, through water shortages through reduced rainfall *(195,197)*. Reduced crop production in turn leads to more food insecurity, as produce becomes more scarce and expensive.

Food access is already a pressing issue in Pakistan. Even though Pakistan currently produces more food than it consumes, 20.5% of its population is undernourished and 39.7% faces food insecurity. The main reason for this is that nearly a quarter of the population cannot afford to buy sufficient or sufficiently nutritious food *(198)*. The average household in Pakistan spends half of their income on food, making many people vulnerable to rising produce prices *(199)*.

5.1.2. Intervention options

There are various options to confront food insecurity induced by droughts. Important adaptation actions include climate monitoring and setting up and improving EWS *(196,200)* and building infrastructure that uses water efficiently *(195)*. Within agricultural practice, proposed actions are the use of sustainable practices, the development and use of crops with a high heat tolerance, a shift to later sowing, optimizing crop calendars, and the use of highly efficient irrigation systems *(195,196,201)*.

5.1.3. Analysis of health co-benefits

In our pilot-testing of the framework, we have considered a scenario in which temperatures in Pakistan are expected to rise by 0.5 °C in 2040 compared to the beginning of the century, resulting in an 8–10% loss in land productivity across all crops *(202)*. Using rice for our assessment, being one of the most important crops in terms of production and consumption in Pakistan, we have consulted the FAOSTAT[f] database and retrieved the total number of hectares of rice cultivated in Pakistan in 2018, as well as the tonnes produced in the same year (2 810 030 ha and 10 802 949 tonnes, respectively). The productivity loss due to climate change results in 972 265 tonnes of rice production not being realized, at the current production level. The foregone revenue from production reaches US$ 187 452 771.

We then considered the system of rice intensification (SRI), a CSA practice that increases the productivity of irrigated rice by modifying the management of nutrients, plants, soil and water (e.g. by applying water intermittently, by using integrated pest management rather than herbicides, or by spacing rice seedlings farther apart on a regular grid rather than randomly) *(203,204)*. It has been estimated that SRI increases yield by 43% on average *(205)*.

Considering the current land productivity (3.84 tonnes/ha) and the one expected with climate change impacts under SRI production (5.15 tonnes/ha), the land area that would need to adopt SRI practices to fully offset the forecasted impacts of climate change is 746 115 ha.

The capital cost of implementing SRI amounts to 52 CFA per kg of rice *(206)*. This value corresponds to US$ 90/tonne, which multiplied by 972 265 (tonnes of rice that would be lost considering a 0.5 °C increase) is equal to US$ 87 503 850 (Table 10).

Table 10. Savings from SRI, considering exclusively crop production

Capital cost of SRI	US$ 87 503 850
Avoided costs	US$ 187 452 692
Net benefit	US$ 99 948 842

As Table A2.8 shows, the avoided cost (i.e. avoided loss of revenue) is larger than the cost of the intervention, even when considering a 1-year time period, or the short-term impact of the CSA. The BCR of the intervention is 2.14.

If we add to this calculation the health co-benefit generated by reducing the cost of malnutrition, the economic viability of the investment increases further. The Government of Pakistan (2021a) *(196)*, indicated that the annual average economic cost of climate change in the country amounts to US$ 1.59 billion, and that one sixth of it is attributable to malnutrition (roughly US$ 265 million, estimated as loss of income). In other words, considering that the total malnourished population of Pakistan is more than 55 million people, the annual economic costs (in US$/person) amount to US$ 4.8. Further, the cost of malnutrition is expected to increase in the future with the strengthening of climate impacts.

[f] https://www.fao.org/faostat/en/#data

We estimate that if the increase in rice production originating from SRI were to be used to mitigate the impact of climate change on nutrition, the investment would generate economic benefits per person in the range of US$ 1.8 to US$ 3.4 when considering either the net benefit of the project or total avoided cost of climate impacts. This is to be compared with an investment of US$ 1.6 per person. Table 11 summarizes the estimated costs, benefits and avoided costs of SRI in Pakistan.

Table 11. Estimated costs, benefits and avoided costs per person of SRI in Pakistan

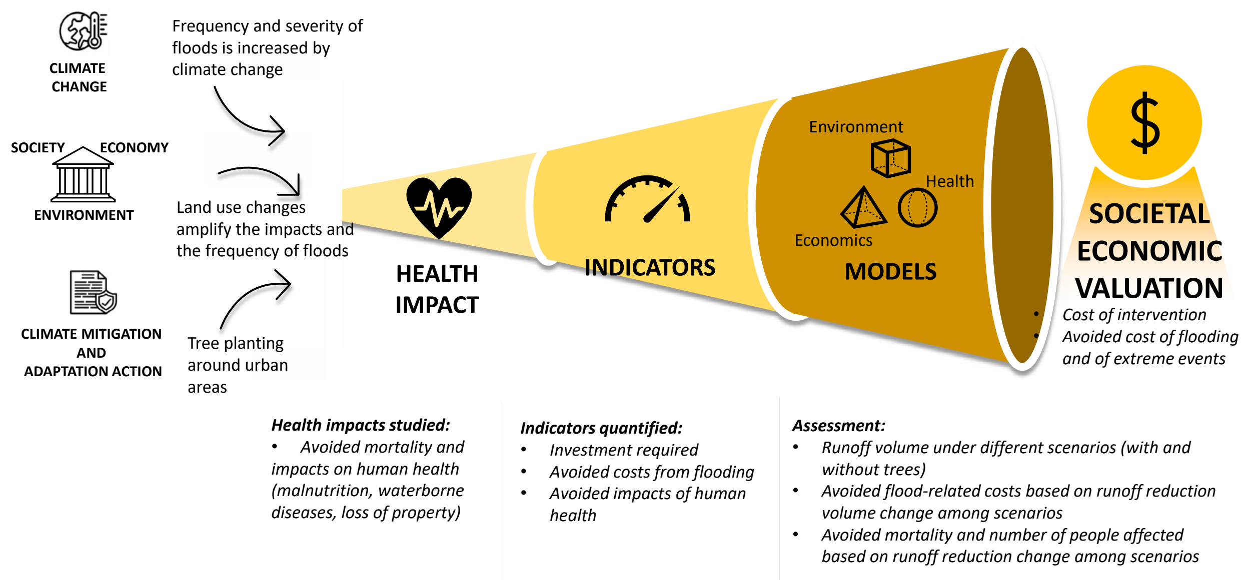
Annual cost of malnutrition due to climate change	US$ 265 000 000
Number of malnourished people	55 000 000
Annual cost of malnutrition per person	**US$ 4.8**
Net benefits of SRI	US$ 99 948 842
Number of malnourished people	55 000 000
Economic benefits of SRI per person	**US$ 1.8**
Total avoided cost of SRI	US$ 187 452 692
Number of malnourished people	55 000 000
Avoided cost of SRI per person	**US$ 3.4**

Finally, to assess the impact of increased rice production on nutrition specifically, the nutritional deficiencies of a target group of the population could be considered. This would allow to determine what would be the best crop mix to support with CSA with the goal of improving nutrition at the local level. In the case of rice, the production increase expected from SRI is forecasted to generate every year additional nutritional inputs: e.g. it will generate 3500 billion additional kCal. Considering that in Pakistan there are 55 million malnourished people, the daily additional kCal for this vulnerable group would correspond to 173.39 kCal, as shown in Table A2.10. Besides, the production increase from SRI is forecasted to generate the following nutritional elements (total annual grams and total grams per day per person):

- Proteins: 63 billion g, 3.15 g
- Fats: 4.9 billion g, 0.24 g
- Carbohydrates: 780 billion g, 38.64 g
- Saturated fatty acids: 970 million g, 0.05 g
- Monounsaturated fatty acids: 1.9 billion g, 0.1 g
- Polyunsaturated fatty acids: 970 million g, 0.05 g
- Sugar: 2.9 billion g, 0.15 g

5.2. Adaptation Action 2: Planting trees for flood mitigation

Fig. 9. Customization of the conceptual framework to tree planting for flood mitigation



Step 1 **Development impact on health**: land clearing for the expansion of residential areas and agriculture have resulted in more frequent – and amplified impacts of – flood events.

Step 2 **Climate change impact on health**: climate variability has led to increased risk and severity of floods, with stronger and more frequent extreme precipitation events, impacting a larger number of people over time.

Step 3 **Climate action considered**: planting trees around urban areas, where they provide protection against floods (adaptation goal) and increase carbon sequestration (mitigation goal).

Step 4 **Indicators quantified**: investment required, avoided costs from flooding, avoided mortality and impacts on human health (malnutrition, waterborne diseases, loss of property).

Step 5 **Models utilized**: spatial models (InVEST) to assess runoff reduction based on land cover changes.

5.2.1. Overview

The South Asian region has been vulnerable to floods for a long time. Due to its geographical location combining monsoon rains and ice melting on nearby mountain ranges, Pakistan is one of the countries most at risk of flooding. Since the 1960s, the country has experienced 19 major flooding events, the 2010 super flood alone killing close to 2000 people and causing damage of US$ 10 billion *(195,207,208)*. Climate change is projected to further increase floods in Pakistan through more concentrated rainfall and glacier melting *(195,209)*.

Floods often have detrimental consequences. Immediate impacts include lost lives and injuries, damage of property and a severe disruption of everyday life and economic activity as people have to leave their homes and/or are unable to commute to work *(210)*. Food production is often severely affected by floods through the loss of seeds, crops and livestock as well as the creation of stagnant water bodies that hinder the growing of crops *(211)*. Furthermore, floods can cause large damage to infrastructure. Transportation is often strongly limited through roads being underwater and others being inaccessible. Many roads and bridges are also marred or destroyed. This in turn leads to limited vehicle circulation that has a negative impact on economic activity and prompts supply crunches *(212)*. Moreover, floods damage both energy and sanitation systems, prompting further negative impacts like the spread of waterborne diseases *(213)*.

5.2.2. Intervention options

Adaptation actions to the damages to infrastructure caused by floods include general measures improving and establishing draining systems, setting up storage containers and building dams *(214)*. An especially fruitful measure against damage to infrastructure from floods is planting trees around urban areas as they provide protection against floods while also mitigating climate change through absorbing carbon dioxide.

5.2.3. Analysis of health co-benefits

We used a spatially explicit model (InVEST Urban Flooding Model) to generate estimates of water runoff retention volumes (m^3) under a given rainfall event. We used two land cover maps, using Islamabad as the study area. The first one shows Islamabad's actual geography in 2019 (LULC BAU), while the second one (LULC trees) includes urban trees placed around the city. Table 12 summarizes the main output of the InVEST urban flooding model, indicating that the total runoff retention volume in the study area with a rainfall event of 200 mm of precipitation. The table shows that the total runoff retention volume would increase by more than 12% with tree planting covering an area of 30 645 ha.

Table 12. Runoff retention statistics

LULC scenario	Total runoff retention volume (m^3)	Difference between LULC trees and LULC BAU (%)
LULC BAU	64 252 934.72	12.30
LULC trees	72 158 136.63	

To quantify the monetary impacts of increased runoff retention, we retrieved the average economic impacts, in US$ millions, of major floods in Pakistan from 1992 to 2012 *(215)*. Firstly, we calculated the average economic impacts in Islamabad based on the share of the population living in the capital city compared to the total population of Pakistan. Secondly, we assumed that if tree planting efforts can increase water retention by 12.30%, then the average economic impacts of flooding during those years can be reduced by the same proportion, which would correspond to US$ 2.11 million annually in avoided flood-related costs. If we assume that the average lifetime of trees is 30 years, then the total avoided costs would amount to US$ 63.34 million up to 2050. We also calculated that the avoided economic costs from extreme events would amount to US$ 18.45 million, assuming that a precipitation event similar to what happened in 2010 occurs every 10 years over the next 30 years.

Considering that a project of restoring 3 500 000 ha of land into forest is currently under way in Pakistan, and that this project is expected to cost US$ 750 million *(216)*, we calculated the total cost of planting urban trees in Islamabad at US$ 6 566 786 (assuming that 30 645 ha of trees will be planted).

Table 13 compares the cost of tree planting to the avoided costs the investment would generate by mitigating flood risk.

Table 13. Avoided economic costs of flood impact on infrastructure with tree planting (30 years)

	US$ over a 30-year period
Avoided costs from flooding	US$ 39 110 310
Avoided costs from extreme events	US$ 18 450 000
Total avoided cost	**US$ 57 560 310**
Investment for tree planting in Islamabad	US$ 6 566 786
Net savings	**US$ 50 993 524**

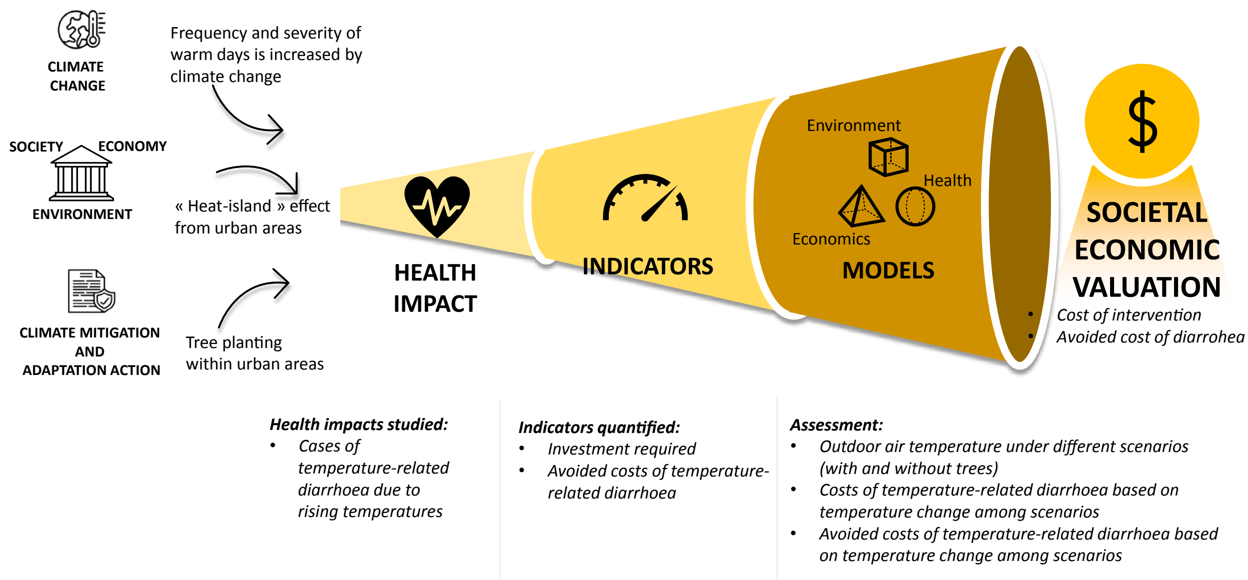
Concerning the impacts on human health, we retrieved the number of average deaths caused by major floods in Pakistan from 1992 to 2012 *(215)*. We calculated the average lives lost in Islamabad (4.25) based on the share of the population living in the capital city compared to the total population of Pakistan. Assuming that if tree planting effort can increase water retention by 12.30%, then the average lives lost due to flooding during those years can be reduced by the same proportion, which would correspond to 0.52 lives annually. If we assume that the average lifetime of trees is 30 years, then the total avoided deaths would be 15.7 up to 2050.

We also considered the number of affected people (20 million) during the 2010 flood event that occurred in Pakistan. Impacts include destruction of homes, crops and infrastructure, leaving millions vulnerable to malnutrition and waterborne diseases *(217)*. Scaling this to Islamabad, 12 300 people could be saved from the negative consequences of a large flood event should trees be planted at the edge of the city.

Considering the investment for tree planting in Islamabad (US$ 6 566 786), and the estimated number of people that will avoid the negative consequences of flooding (12 300), we can estimate that the cost of avoiding the impact of flooding would amount to approximately US$ 534 per person. On the other hand, this investment is expected to avoid flood impacts over the cost of the next 30 years, and therefore the cost-effectiveness of the investment is high. If we consider the potential occurrence of three similar events in the next 30 years, the cost per person declines to US$ 178. If we consider the potential avoided impact from smaller flood events, then the cost per person could decline to US$ 10–US$ 20 per person over the course of 30 years.

5.3. Adaptation Action 3: Planting trees in cities for heat mitigation

Fig. 10. Customization of the conceptual framework to tree planting in cities for heat mitigation



Step 1 **Development impact on health**: the expansion of urban areas has resulted in the creation of heat island effects.

Step 2 **Climate change impact on health**: climate variability has led to increased temperature and in increased frequency and severity of warm days.

Step 3 **Climate action considered**: planting trees within urban areas, for carbon sequestration (mitigation goal) and air temperature reduction (adaptation goal).

Step 4 **Indicators quantified**: investment required, avoided costs of temperature-related cases of diarrhoea.

Step 5 **Models utilized**: spatial models (InVEST) to assess temperature reduction based on land cover change.

5.3.1. Overview

Due to climate change, temperatures in Pakistan are rising and droughts and heatwaves are occurring more frequently *(196)*. While the country currently has 150 days of warm spells a year, their number is projected to increase to 350 under a high-emissions scenario and to 185 under a low-emissions scenario until 2100 *(209)*. Temperatures are also projected to rise more steeply in Pakistan than in the world on average *(200)*. Heat is already causing adverse effects in Pakistan. A severe heat wave occurring in 2015 alone killed over 1200 people, while around 65 000 suffered from heat strokes *(218)*.

Rising temperatures in Pakistan have a variety of negative impacts. Besides causing mortality and morbidity, rising temperatures often contribute to droughts that severely affect agricultural production. Moreover, they increase the risk for wildfires and lead to glacier melting, which in turn increases flooding and its negative impacts *(200)*. In cities, increased temperatures can have an especially adverse effect on human health since they are combined with negative effects of air pollution on respiratory systems *(218)*. Cities are also prone to the urban heat island effect, higher temperatures from a lack of non-sealed land to absorb heat *(195)*. Apart from that, many inhabitants of urban areas in Pakistan live in slums with no adequate cooling of buildings, putting them acutely at risk for heat strokes *(200,219)*.

5.3.2. Intervention options

Adaptation actions to rising temperatures in Pakistan include shifts in agriculture to more efficient watering and sowing, improving and establishing early hazards warning systems, as well as improving the access to health care *(195,200)*. To reduce heat in cities, creating more green spaces on the ground and on rooftops have generally proven to be a successful measure. One particular strategy is the planting of trees that cool their surroundings through evapotranspiration and providing shade *(220)*.

5.3.3. Analysis of health co-benefits

As in the case of flood risk mitigation, we use a spatially explicit approach to estimate the potential impact that tree planting in the city centre can have in reducing air temperature. Trees in this case are planted in correspondence to roads, especially in residential areas. Table 14 summarizes the main output of the InVEST urban cooling model, which is the average temperature in the study area. The table indicates that the average temperature would decrease by 0.7 °C from the current landscape (LULC BAU) to the one where trees are planted in the city (LULC trees).

Table 14. Urban cooling statistics

LULC scenario	Average temperature value (°C)	Difference between LULC trees and LULC BAU (°C)
LULC BAU	34.3	-0.7
LULC trees	33.6	

The Government of Pakistan indicated that a 1 °C increase in temperatures leads to a 4.6% increase in the cases of diarrhoea *(196)*. Based on this information we are able to calculate the avoided costs of temperature-related diarrhoea from tree planting, considering that an avoided temperature increase of 0.7 °C will avoid a 3.22% increase (i.e. 70% of 4.6%) in the cases of diarrhoea.

Starting from the baseline costs (lower and higher bounds) of temperature-related diarrhoea provided by the Government of Pakistan *(196)* (Table 15), we calculated the expected annual cost reduction due to tree planting, as well as the total annual costs in 2050 in the absence of tree planting (assuming that the average temperatures will increase by 0.7 °C in the medium-to-long term from the baseline, for simplicity). Table 15 also shows the cumulative cost reduction due to tree planting in Pakistan.

Table 15. Cumulative cost reduction due to tree planting

	Baseline – economic costs of temperature-related diarrhoea	Total annual costs in 2050 in the absence of tree planting	Expected annual cost reduction due to tree planting in 2050	Cumulative cost reduction due to tree planting by 2050
Temperature-related diarrhoea – Lower bound	US$ 122 530 000	US$ 126 475 466	US$ 3 945 466	US$ 57 209 257
Temperature-related diarrhoea – Upper bound	US$ 316 550 000	US$ 326 742 910	US$ 10 192 910	US$ 147 797 195

Table 16 summarizes costs and health co-benefits. To obtain the cumulative cost reduction due to tree planting in Islamabad, we considered the share of the population living in the capital city compared to the total population of Pakistan. This estimate may be conservative, considering that heat extremes are more frequent in urban areas than in rural ones.

The total cost of planting trees in urban areas amounts to more than US$ 6.5 million (assuming that 30 481 ha of trees will be planted). The number of trees planted is similar to what is assumed in the flood mitigation exercise, for ease of comparison.

Overall, the tree planting costs more than the health co-benefits it generated. On the other hand, the benefits of tree planting are many and varied. First, while we only considered the cost reduction in relation to temperature-related diarrhoea, there are many additional health benefits that could be estimated. Further, there are several other, non-health-related benefits to consider. Specifically, trees absorb carbon dioxide which leads to reduced GHGs and air pollution where they are planted *(219)* (EPA, 2012). Thus, planting trees to reduce heat in cities is not only an adaptation action to climate change but also to mitigate it. Through improving air quality, planting trees has a variety of health benefits. The measure helps to prevent respiratory diseases, cardiovascular damage, fatigue, headaches and anxiety, irritation of the eyes, nose and throat, damage to reproductive organs, nervous system damage as well as cardiovascular diseases in development stages of infants, cancer later in life and negative impacts on cognitive performance (Annex 1). Furthermore, by providing shade, trees reduce exposure to UV rays, lowering the risk of vision impairments and skin cancer *(220,221)*. Non-health-related co-benefits include reduced energy expenditure for the cooling of buildings and reduced costs for pavement maintenance *(220,222)*. Finally, planting trees is linked to a general enhancement of the quality of life and has been associated with reduced crime and increased value of property *(220,223,224)*. With this in mind, the avoided costs from temperature-related diarrhoea are still relevant, and amount to about 10% of the investment required for tree planting (when using the upper bound estimate, which seems more realistic).

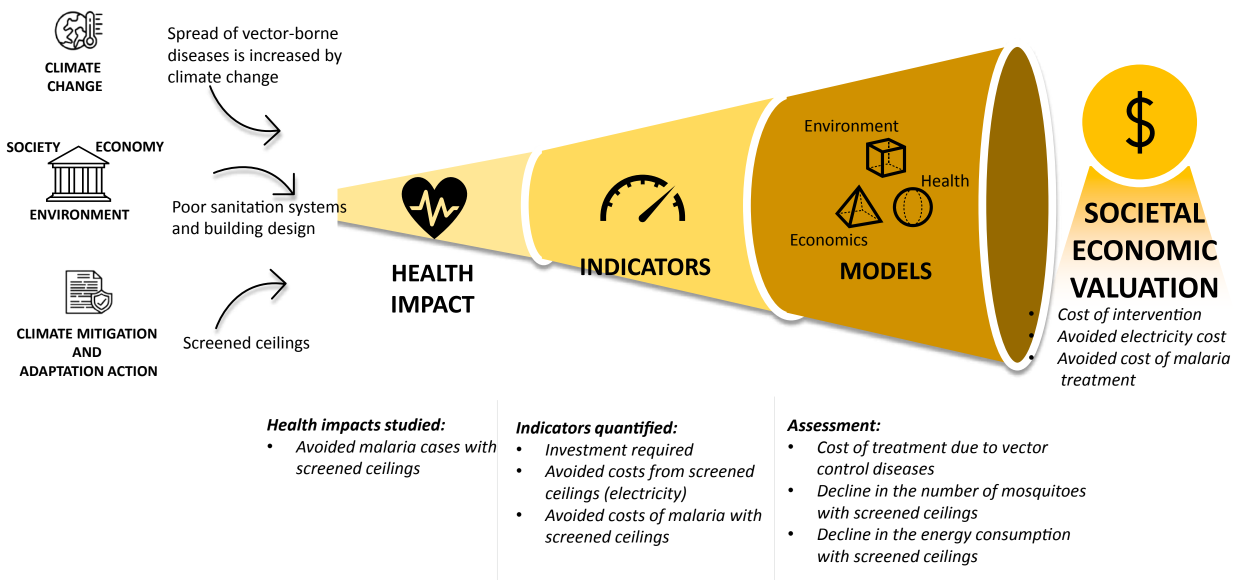
Table 16. Avoided economic costs of temperature-related diarrhoea with tree planting

	Cumulative cost reduction due to tree planting (per person)	Cumulative cost reduction due to tree planting (whole population of Islamabad)
Temperature-related diarrhoea – Lower bound	US$ 0.26	US$ 262 867
Temperature-related diarrhoea – Upper bound	US$ 0.67	US$ 679 104
Investment for tree planting in Islamabad		US$ 6 531 643
Savings – Lower bound		US$(6 268 776)
Savings – Upper bound		US$(5 852 538)

In our study, we concluded that reforestation efforts in Islamabad may avoid an increase of 3.22% of the cases of diarrhoea in the capital city, which would correspond to 102.35 cases annually. If we consider that the average lifetime of trees is 30 years, then the reforestation project would avoid 3070.43 cases, based on a study that reported the cases of diarrhoea in the Sindh province in 2014 *(225)*.

5.4. Adaptation Action 4: Improved building design

Fig. 11. Customization of the conceptual framework to improved building design



Step 1 **Development impact on health**: poor sanitation systems and lack of measures in building design can exacerbate the impacts of vector-borne diseases.

Step 2 **Climate change impact on health**: climate variability has led to increased temperature and flooding, which increase the spread of vector-borne diseases.

Step 3 **Climate action considered**: screened ceilings in buildings can reduce the spread of vector-borne diseases and reduce electricity consumptions (both an adaptation and a mitigation goal).

Step 4 **Indicators quantified**: investment required, avoided costs of malaria treatment, and avoided energy costs.

Step 5 **Models utilized**: data and results of studies found in the literature related to energy use in buildings, and prevalence of malaria in relation to building characteristics.

5.4.1. Overview

In Pakistan, climate change is projected to increase temperatures and lead to more frequent flooding *(195)*. Both of these factors worsen the spread of vector-borne diseases in the country. Because vectors are cold-blooded animals, they generally thrive better in warmer climates and higher temperatures are expected to increase both the size of vector populations and the rate at which the germs they transmit develop *(226)*. Floods produce stagnant bodies of water that are suitable breeding grounds for vectors *(227)*. This issue is made worse by the fact that many areas in Pakistan lack well-functioning sanitation systems *(200,219,228)*. Vector-borne diseases already pose a significant health problem in Pakistan. It has 300 000 confirmed and 1 million estimated cases of malaria each year *(229)*.

5.4.2. Intervention options

There are various strategies to combat the spread of vector-borne diseases. Vector-control interventions include environmental management to reduce breeding grounds, biological controls to kill larvae, chemical methods to kill vectors, and personal protection strategies against bites *(230)*. The most prevalent vector-control methods are insecticide-treated nets as a personal protection strategy and indoor residual spraying as a chemical method *(231)*. Further action to reduce vector-borne diseases include more investment in research on health-system resilience, vector sampling tools, and new vector-fighting technologies *(232)*. Within vector-controlling, the strategy of "building the vector out", improving housing design to limit vectors from entering is very effective. Measures include reducing waste serving as breeding grounds, improving toilet facilities, and closing cracks as well as covering windows, doors and ceilings with screens *(233,234)*.

5.4.3. Analysis of health co-benefits

To carry out an assessment of the impact of improving buildings, and especially investing in screened ceilings, we have integrated information from different domains. First, US$ 49.62 is the global average economic cost of treating one person per year due to vector control diseases *(235)*; second, 3.5 million per year is the number of annual cases of malaria in Pakistan, according to the Directorate of Malaria Control of Pakistan (DMC); third, the decline in the number of mosquitoes in houses with screened ceilings is 47% *(234)*; fourth, US$ 10 per person is the economic cost of screened ceilings *(234)*; fifth, screened ceilings also result in a 10% decline in energy costs (lower estimate) *(236)*.

From the information shown above, we estimate that the costs of ceiling, the annual avoided costs of malaria and avoided energy cost will amount to US$ 1 862 385, US$ 117 734, and US$ 375 053, respectively in one year of implementation (Table 17). Assuming a lifetime of screened ceiling of 20 years, the total avoided costs become larger than the investment required, when considering savings on both energy and cost of malaria. In other words, investing US$ 1 in screened ceiling would allow to generate US$ 5.29 in avoided costs over the course of 20 years.

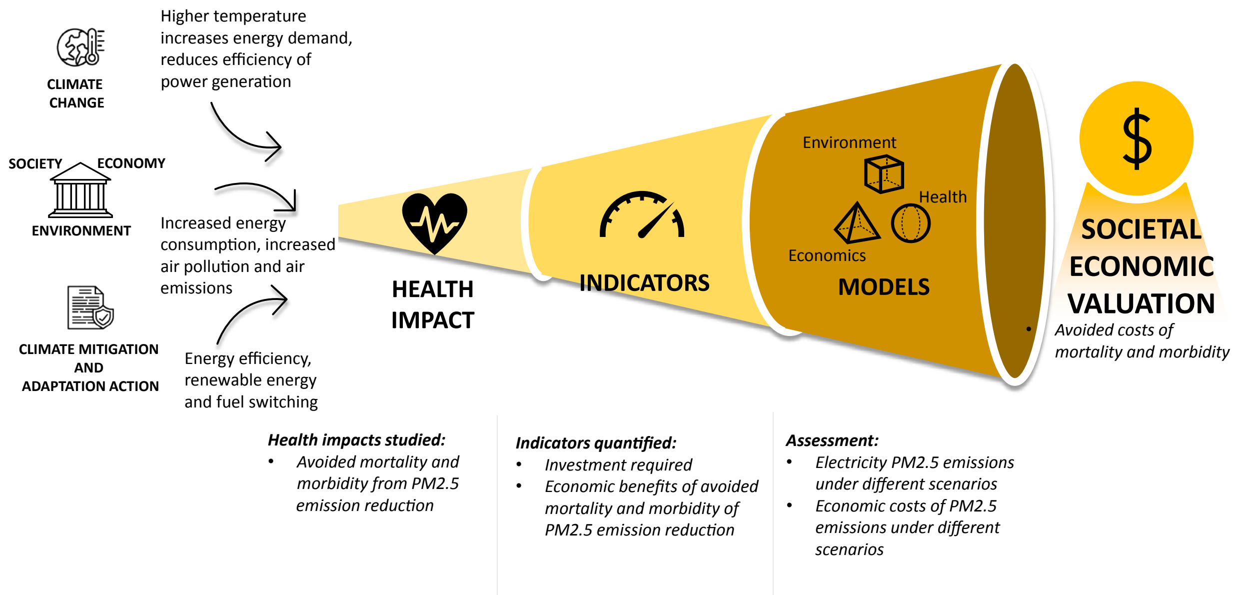
Table 17. Capital and avoided costs of screened ceiling

	1 year		20 years
	Pakistan	Islamabad	Islamabad
Screened ceiling cost	US$ 405 321 101	US$ 1 862 385	US$ 1 862 385
Avoided costs of electricity	US$ 25 623 000	US$ 117 734	US$ 2 354 671
Annual cases of malaria	3 500 000	16 082	321 639
Annual cost of malaria	US$ 173 670 000	US$ 797 986	US$ 15 959 715
Avoided cost of malaria with screening	US$ 81 624 900	US$ 375 053	US$ 7 501 066

Even if the cost of implementation is higher than the estimate used for the analysis presented above, and reaches US$ 10 per person rather than per household, the investment would be comparable to the savings. In fact, while the economic costs would amount to US$ 10 150 000, the cumulative avoided costs would reach US$ 9 855 737. Further, installing ceiling screens to combat vector-borne diseases is likely to especially benefit low-income households that often live in poor housing. Moreover, it creates jobs and stimulates investment in the housing sector *(237)*. It also reduces electricity use *(236)*.

5.5. Mitigation Actions: Energy efficiency, renewable energy and fuel switching

Fig. 12. Customization of the conceptual framework to energy efficiency, renewable energy and fuel switching



Step 1 **Development impact on health**: increased energy consumption, increased air pollution and air emissions. Reliance on fossil fuels for power generation exacerbates air pollution and results in high price variability.

Step 2 **Climate change impact on health**: higher temperature increases energy demand, reduces efficiency of power generation.

Step 3 **Climate action considered**: energy efficiency, renewable energy and fuel switching (climate mitigation goal).

Step 4 **Indicators quantified**: investment required, PM2.5 emission reduction, avoided costs of morbidity and mortality.

Step 5 **Models utilized**: energy demand and power generation models, providing inputs to the estimation of morbidity and mortality.

5.5.1. Energy efficiency

Overview

Pakistan's economic development priorities facilitate an increased energy demand; the country is experiencing a demand–supply gap of 3000 MW *(238)*. At the same time, energy is the biggest source of GHG emissions in Pakistan, having produced 218.9 MT CO_2 equivalent in 2018 alone *(238)*. Energy use contributes to outdoor air pollution in leading sectors such as industry, transport and agriculture *(239)*. Ageing infrastructure contributes to inefficient energy use in key sectors *(240)*.

Recent WHO estimates indicate that together, outdoor and indoor air pollution result in a mortality rate of 173 deaths per 100 000 population due to respiratory diseases, cardiovascular disease and cancer *(124)*. Air pollution reduces Pakistanis' average life expectancy by 2.7 years and up to 5.3 years in some large cities such as Lahore *(239)*. PM2.5 concentrations have increased to the extent that today, almost 100% of Pakistanis live in areas where PM levels exceed WHO-recommended threshold of 10 μg/m^3 *(239)*.

Intervention options

Reducing energy consumption through energy efficiency measures can help reduce GHG emissions and air pollution levels. Pakistan's development strategies and action plans already prioritize energy efficiency measures as the National Energy Conservation and Efficiency Act *(241)* aims to contribute approximately 6.5% of the total emission reduction (compared to BAU) by 2023 *(240)*. The National Energy Efficiency and Conservation Authority (NEECA) and the Pakistan Engineering Council (PEC) are revising the Building Code of Pakistan to achieve the 0.5 MTOE energy saving target. Compliance enforcement is set to take effect before the end of 2021 *(240)*. NEECA strategic plan includes training and capacity building, including for energy auditors. Since 2021, new mandatory minimum energy performance standards (MEPS) for energy-efficient LED lighting have been introduced in the framework of the Delivering the Transition to Energy Efficient Lighting in Residential, Commercial, Industrial, and Outdoor Sectors project *(242)*. NEECA is also developing such standards for electric motors and air conditioners *(238)*.

5.5.2. Renewable energy

Overview

Fossil fuels occupy a prominent place in Pakistan's energy supply. The share of oil, gas and coal in the energy mix increased from 60% in 2015 to 62% in 2019, while the share of non-hydro renewables (wind and solar) increased only from 0.1% to 0.3% in that period *(105)*. As noted above, Pakistan's continued reliance on fossil fuels results in GHG emissions that contribute to air pollution, exacerbating the toll from respiratory and cardiovascular disease, cancer and other diseases. Increasing the share of renewable energy is therefore a key strategy for addressing those negative health effects.

Intervention options

In 2020, the then Prime Minister announced a target of 60% of the country's electricity mix from renewables by 2030 (a share of 30% hydro and 30% from other renewables such as wind, solar, etc.) and a phase-out of coal-burning power plants *(243)*. The alternative and renewable energy (ARE) Policy (2019) provides incentives for investments in renewables including exemptions for corporate income tax, import duties and a general sales tax (GST) on the purchase of equipment for renewable energy projects *(244)*. However, growth in renewable energy in Pakistan has been constrained by fossil fuel subsidies, lack of a carbon price, and poor grid integration of renewable energy sources such as wind and solar.

While Pakistan has made efforts to reform its fossil fuel subsidies, resulting in a 76% decline from 2010 levels *(245)*, this policy has been inconsistent. For example, in 2020, the government announced price reductions to petroleum products *(243)*, meaning a de facto re-implementation of the subsidies. In addition, the fact that the bulk of energy generation has been based on gas, oil and coal *(245)* means that general electricity subsidies include support for fossil fuels. It is important to avoid setbacks in fossil fuels subsidy reform to give consistent price and investment signals, in addition to maintaining the health and climate benefits of the reforms.

Putting a price on carbon can also help address the negative externalities of fossil fuel generation and use. In addition to helping reduce air pollution, a carbon tax can help finance renewable energy projects *(246)*. Pakistan has taken steps towards introducing a carbon price. In 2018, the Ministry of Climate Change undertook a technical study on a possible carbon pricing instrument (IISD, 2018) *(61)*. The report recommended implementing a domestic emissions trading scheme (ETS), and the updated NDC mentions ongoing national consultations on carbon pricing instruments *(238)*.

Finally, hydroelectric currently forms the largest share of renewable energy generation in Pakistan. Increasing the share of variable renewable energy (VRE) sources such as wind and solar will require a feasibility analysis of the capacity of the grid. VRE integration will also require significant investments and planning to address matching of energy supply and demand, storage and other aspects of VRE deployment *(238)*.

5.5.3. Fuel switching

Overview

Pakistan's recent strategic decision to reduce its reliance on coal is an important step towards a carbon-neutral future; however, there are other important contributors to energy-related morbidity and mortality. According to Buonocore et al. (2016) *(4)* in 2008 coal was the biggest contributor to harmful health impacts from PM2.5 emissions in the United States. Since then, transition from coal to gas has brought about a 12% reduction in GHG emissions; however, emissions from biomass and wood combustion from residential and commercial buildings and industrial boilers continue to present significant health threats *(4)*. PM2.5 emissions associated with biomass-based fuels contribute to respiratory diseases, cancers, pregnancy complications, cardiovascular diseases, and other negative health impacts *(247)*. Using wood for cooking also contributes to deforestation *(247)*, which results in additional negative health effects.

The majority of households in Pakistan rely on efficient solid biofuels with low energy content *(200)* (IFCR, 2021). Domestic natural gas reserves are forecast to decline in Pakistan, which may increase the rural population's reliance on biomass *(248)*. Already, usage of biomass is responsible for nearly 40% of all deaths from respiratory diseases, cardiovascular diseases and cancers among adults, especially women, and child deaths related to acute lower respiratory infections (WHO, 2015c). Switching from polluting fuels to cleaner fuels is therefore needed to reduce PM2.5 exposure and effects *(247)*. However, reducing biomass use can be challenging, in particular in rural areas of Pakistan where households experience fuel scarcity and spend a larger share of income on fuels compared to urban populations *(248)*.

Intervention options

To reduce households' reliance on biomass fuels, Pakistan's energy regulator could increase access to liquefied natural gas (LNG) in rural areas *(248)*. Electrification of energy use will improve indoor air quality and can reduce GHG emissions and air pollutants. It is necessary, however, to avoid increasing outdoor air pollution from fossil fuel-based electricity generation. The transition pathway may, in some circumstances, prioritize liquefied petroleum gas (LPG) for clean cooking and solar lamps or solar-based mini-grids to ensure reliable, safe and healthy access to energy for lower-income households.

In addition, the Government of Pakistan needs to encourage reforestation due to forest cover depletion as a result of widespread use of firewood *(248)*. As discussed in this report, Pakistan's current efforts to address deforestation (e.g. through the Billion Tree Tsunami initiative) are effective and cost-efficient and need to be continued and expanded.

5.5.4. Analysis of health co-benefits

Reducing the use of fossil fuels can generate positive health outcomes. Energy efficiency measures can help reduce both non-communicable diseases such as respiratory illnesses, and communicable diseases that are transmitted due to energy-inefficient building designs. Increasing the share of renewables in sectors such as power generation, industry, transport and the residential sector can help Pakistan reduce GHG emissions from energy and therefore, morbidity and mortality from cardiovascular disease, respiratory diseases and cancers. Fuel switching can help reduce PM2.5 and other associated chemicals including SOx, NOx and ozone in ambient air, which will reduce mortality and DALYs from cardiorespiratory diseases and pregnancy losses.

To quantify the economic value of morbidity and mortality in Pakistan, we have used forecasts for energy and GHG emission reduction developed for the NDC report *(238)*.

On the economic side, we started from the following information: the U.S. Environmental Protection Agency (2013) *(249)* provides monetary values for combined impacts on mortality and morbidity per tonne of directly emitted PM2.5. Next, we found that health costs of morbidity generally amount to 10–20% of the cost estimate that includes both morbidity and mortality *(250)*. This allows us to disaggregate the cost of morbidity and mortality.

We then calculated the total PM2.5 emissions from energy consumption and power generation in Pakistan under different scenarios, as shown in Table 18. We also calculated the difference in emission within each scenario between 2030–2020 and 2050–2020.

Table 18. Total PM2.5 emissions from energy consumption and power generation

Scenario/pollutant	Unit	2020	2030	2050	Difference 2030–2020	Difference 2050–2020
NDC reference	Tonne/year	664 847	805 248	949 134	140 401	284 287
Business as usual (BAU)	Tonne/year	664 847	763 467	797 905	98 620	133 058
Current ambition	Tonne/year	664 847	708 416	562 111	43 569	-102 736
High ambition	Tonne/year	664 847	621 095	337 961	-43 752	-326 886

By multiplying the cost per tonne of directly emitted PM2.5 by 10%, which is the share of morbidity costs, and by the difference in emissions within each scenario between 2030–2020 and 2050–2020 (Table A2.6), we were able to calculate the morbidity costs of emissions from the energy sector in Pakistan under different scenarios, as shown in Table 19.

Table 19. Economic costs of PM2.5 emissions under different scenarios

Scenario/pollutant	Unit	Difference 2030–2020	Difference 2050–2020
NDC reference	US$	2 808 020 000	5 685 740 000
Business as usual (BAU)	US$	1 972 400 000	2 661 160 000
Current ambition	US$	871 380 000	-2 054 720 000
High ambition	US$	-875 040 000	-6 537 720 000

In addition to the annual morbidity cost, we estimated the cumulative value of climate mitigation investments up to 2030 and 2050. Table 20 shows the cumulative economic benefits of PM2.5 emission reduction when compared to the NDC reference scenario.

Table 20. Cumulative economic benefits of PM2.5 emission reduction from the baseline

Average economic benefits	2020–2030	2020–2050
Business as usual (BAU)	US$ 4 124 173 750	US$ 43 625 015 000
Current ambition	US$ 9 667 287 500	US$ 109 107 137 500
High ambition	US$ 18 974 901 250	US$ 184 008 721 250

As Table 21 shows, we calculated the economic co-benefits of avoided morbidity compared to the NDC reference scenario in 2030 (data taken from Table 19). Furthermore, Table A2.9 also shows the economic co-benefits of avoided mortality compared to the NDC reference scenario in 2030 *(233)*, using the same scenarios considered for the estimation of morbidity co-benefits.

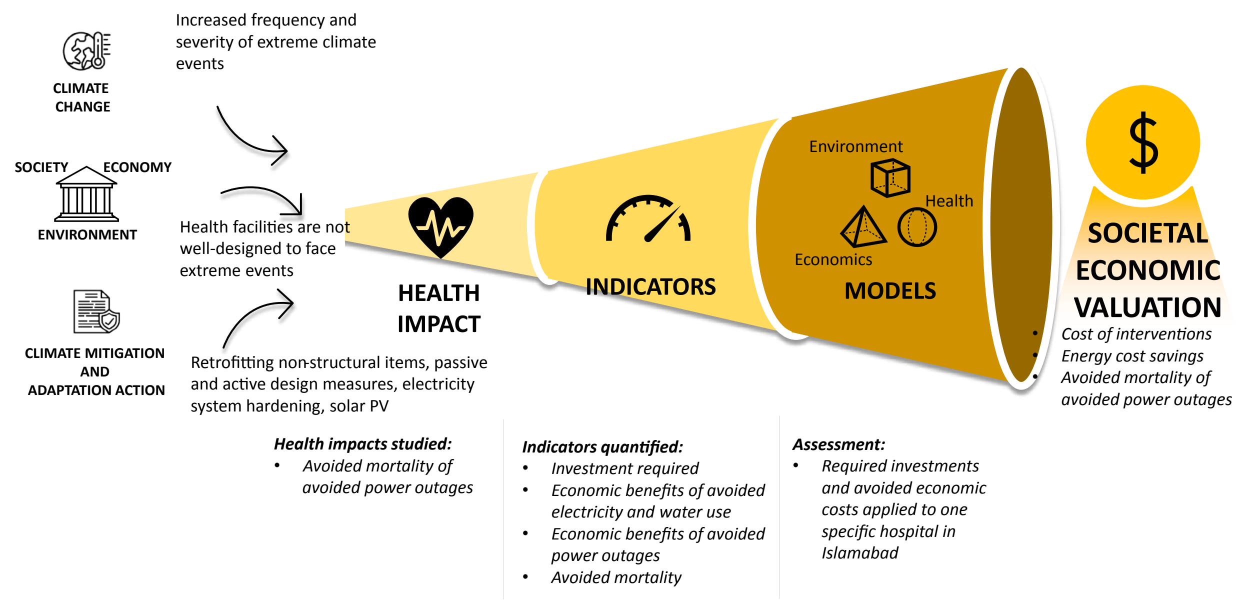
Table 21. Validation of economic co-benefits of avoided morbidity and mortality compared to the NDC reference scenario in 2030

Scenario	Economic co-benefits (morbidity) vs NDC reference in 2030	Economic co-benefits (mortality) vs NDC reference in 2030	Total co-benefit	% of morbidity co-benefits
Business as usual (BAU)	US$ 835 620 000	US$ 2 630 000 000	US$ 3 465 620 000	24.1%
Current ambition	US$ 1 936 640 000	US$ 6 100 000 000	US$ 8 036 640 000	24.1%
High ambition	US$ 3 683 060 000	US$ 10 650 000 000	US$ 14 333 060 000	25.6%

Finally, we can compare the cost of realizing Pakistan's ambition for emission reduction from the NDC to the cumulative health co-benefits of reducing air emissions (Table 20). The cost of energy-related intervention is estimated to be US$ 101 billion by 2030, growing to US$ 166 billion by 2040. The "current ambition" scenario, which represents NDC ambition, would avoid US$ 10 billion by 2030 and up to US$ 110 billion by 2050. Considering that the lifetime of the investment made in the NDC to reduce emissions ranges between 20 and 40 years (reaching 2060), the health co-benefits alone would more than offset the investment required. If we then consider avoided energy costs, job creation and other positive economic benefits resulting from these outcomes, investing in emission reduction is a viable investment, and even more so when considering health co-benefits.

5.6. Combining mitigation and adaptation: climate proofing of health facilities

Fig. 13. Customization of the conceptual framework to the climate proofing of health facilities



Step 1 **Development impact on health**: infrastructure is vulnerable to climate change impacts; it was not designed to withstand climate extremes.

Step 2 **Climate change impact on health**: increased frequency and severity of extreme climate events, increasing vulnerability of health facilities and interruptions of health service delivery.

Step 3 **Climate action considered**: retrofitting non-structural items, passive and active design measures, electricity system hardening (undergrounding), solar photovoltaic (PV) (both representing climate adaptation and mitigation goals).

Step 4 **Indicators quantified**: investment required, avoided costs of energy and water consumption, avoided costs of power outages, avoided mortality.

Step 5 **Models utilized**: data and results of studies found in the literature related to the frequency of power outages, hospital energy use, and impact of climate change on operations.

5.6.1. Overview

Hospitals and other health facilities are at the frontline of climate-induced natural disasters, delivering services to reduce morbidity and mortality while facing simultaneously challenges related to the impacts of climate change on infrastructure *(122)*. In response to increasing frequency and intensity of extreme events, decision-makers should aim for increased resilience. This can be realized by climate proofing health facilities, reducing vulnerability to power and water shortages, extreme wind and damage to transport infrastructure. Climate proofing implies increasing energy and water self-sufficiency, reducing the cost of operations as well as the cost of service, and health service delivery interruptions, while possibly also reducing GHG emissions. As a result, synergies can be found in health facilities that connect climate adaptation to climate mitigation.

5.6.2. Intervention options

Extreme events, such as storms, floods and heatwaves can result in damage to power generation and distribution infrastructure, leading to power outages *(251)*. Damage to road infrastructure instead can limit the access of patients, equipment and supplies to health facilities. Damage to the building can prevent the delivery of health services, and requires a reorganization of operations (e.g. transferring patients to different buildings of a hospital). These are all critical issue for health facilities, and affect both the capacity to delivering health services as well as its cost.

In this assessment we consider (i) retrofitting of non-structural items and (ii) the implementation of passive and active design measures for building resilience, and (iii) the undergrounding of transmission lines or (iv) the use of on-site power generation with solar panels and batteries to reduce the risk of power shortages. We assess the cost of these interventions and compare it with selected benefits. The assessment focuses on the Federal Government Polyclinic Hospital (FGPH) of Islamabad as a case study, whose area covers 13 006 m^2 with a maximum capacity of 545 beds *(252)*.

More details on the specific assumptions used to estimate the outcomes of the investments analysed are presented in Annex 2.

5.6.3. Analysis of health co-benefits

We estimated six separate CBAs, one for each of the four investments considered, implemented in isolation, and two for the portfolio of interventions. Concerning the latter, we have grouped retrofitting and passive design measures, with either electricity system hardening or solar PV with battery storage.

The lifetime of the investments is assumed to be 20 years, and the discount rate used is 5%. Further, we assume that (i) solar PV investment and related outcomes are lower when retrofitting is also considered (due to energy savings). Finally, we have estimated avoided costs and project finance indicators (internal rate of return [IRR], net present value [NPV] and BCR) using two approaches: one that considers the cost of avoided power outages, and one that does not. This is, on the one hand, to estimate the economic viability of solar power and battery storage in relation to energy cost savings exclusively and, on the other hand, to highlight the incidence of power shortage costs in determining the economic viability of electricity system hardening investments.

Table 22 shows the results of the assessment, providing information on the required investment, avoided costs, NPV, IRR, BCR, and payback period. As the table suggests, most interventions are economically viable. Specifically, all financial indicators are positive when considering all potential avoided costs, especially those related to avoided power shortages. On the other hand, when these are not considered, electricity system hardening and solar PV with battery storage are not economically viable. Thus, the consideration of the cost of power outages, as well as the potential impact on mortality, are essential for the economic valuation of these investments.

When reviewing the investment required, the undergrounding of the electricity transmission lines is the most expensive intervention, reaching close to US$ 60 million. On the one hand, when considering the cost of power shortages, this investment is viable, with a BCR of 3.26 and IRR of 49%. On the other hand, in the event in which this intervention is not effective in reducing power shortages, its financial performance (when considering hospital operations alone) would be negative. Solar PV with battery storage shows very similar outcomes: it is economically viable when considering avoided power shortage costs, but the investment is not paid back when considering only energy cost savings. On the other hand, the potential loss is not as high as with the undergrounding of transmission lines. Solar PV and battery storage show an IRR close to 0%, with up to 72% of the investment being paid back over the course of 20 years. It has to be considered that, should the cost of electricity from the grid increase over time, the economic viability of solar PV and batteries would increase. Our assessment assumes instead the price of electricity from the grid remains constant in the future.

Finally, retrofitting non-structural items and design measures are both the cheapest interventions and the most profitable. They both generate a positive a similar NPV (approximately US$ 1.5 million), IRR (around 70%), BCR (around 5.8), and a short payback period (2 years). Overall, these measures represent two convenient solutions to reduce the cost of operations and to increase resilience to certain climate impacts (e.g. strong wind in the case of retrofitting). On the other hand, they provide a minimal contribution (if any) to power shortages.

Table 22. Summary of the CBAs

	Total investment	Avoided costs	NPV	IRR	BCR	Payback period (years)
*** Full CBA 1** (retrofitting, design, undergrounding)	US$ 59 563 132	US$ 233 256 921	US$ 100 717 735	49%	3.26	3
***Full CBA 2** (retrofitting, design, solar PV)	US$ 16 430 484	US$ 243 981 669	US$ 137 668 103	110%	10.61	1
*Electricity system hardening	US$ 58 424 843	US$ 227 520 000	US$ 97 996 048	48%	3.24	3
*Solar PV and battery storage	US$ 15 185 917	US$ 227 520 000	US$ 136 952 283	113%	11.22	1
Full CBA 2 (retrofitting, design, solar PV)	US$ 16 430 484	US$ 16 461 669	US$(4 066 988)	0%	0.72	20
Retrofitting non-structural items	US$ 414 200	US$ 3 113 636	US$ 1 603 546	70%	5.77	2
Passive design measures	US$ 344 659	US$ 2 623 285	US$ 1 354 509	71%	5.84	2
Solar PV and battery storage	US$ 15 185 917	US$ 13 838 384	US$(4 782 808)	-1%	0.64	N/A
Avoided cost of mortality			US$ 4 781 750 per year			

Note: CBAs with * consider the avoided costs of power outages

Finally, when considering the economic value of avoided mortality, the implementation of investments for securing reliable power supply results in a considerable improvement of the economic analysis. We first consider that the FGPH has a maximum capacity of 545 beds *(252)*. Second, we assume that the hospital works at full capacity, and that the average stay of a patient there is 1 month. Third, acknowledging that hospital mortality in Pakistan is 6.2% *(253)*, we assumed that 6.2% of 545 patients at are risk of mortality every month. Fourth, we assume that, for the purpose of economic valuation, 5% of the patients who are at risk of mortality during power outages are in productive age. With these considerations in mind, we conclude that every year around 20 patients hospitalized in the FGPH are in productive age and at risk. When we add that the risk of mortality increases by 43% on days in which health facilities are affected by a power outage for 2 or more hours *(254)*, it means that approximately 9 patients (8.72) in productive age are at risk of mortality due to power shortages every year. This value is multiplied by the VSL in Pakistan, which ranges from US$ 321 813 to US$ 775 193 (i.e. US$ 548 503), to perform the economic valuation of avoided mortality. The result of this multiplication is US$ 4 781 750 per year, as shown in Table 22, and assumes that those patients who do not die, as a result of investments to improve energy security, go on to live till the end-of-life expectancy. We acknowledge that many assumptions had to be made to estimate the economic benefits of investments in undergrounding and solar PV plus batteries, and several elements of uncertainty should be considered. On the other hand, this estimation is provided as an example of the approaches that could be used to estimate indicators that are often overlooked in the context of climate mitigation and adaptation analysis. In this case, we use the VSL, an indicator used regularly in the context of transport assessments but, so far, rarely used for studies such as the one proposed above.

5.7. Lessons learnt and caveats for modelling exercises

This document argues the value of integrating knowledge across fields of research and thematic policy areas. This is important to ensure that policy decisions are made by taking into account information pertaining to direct, indirect and induced outcomes of policy implementation. If the policy analysis performed is systemic, there is a lower risk that side-effects will emerge and there is a higher probability that synergies will be realized. Further, if side-effects are identified before policy implementation, there will be an opportunity to prepare and formulate a policy package that may prevent the emergence of such side-effects.

The above being said, it should be mentioned that knowledge integration is not an easy task. If not performed correctly, as it is the case for any policy assessment, it may result in misleading policy recommendations and a higher risk of failure for policy implementation. With the integration of knowledge across policy domains, it is even more critical that data are validated, assumptions are cross-checked for consistency, and results are analysed in relation to their plausibility from a sectoral and systemic point of view. Computational reproducibility, or the possibility for other researchers to reproduce the analysis performed, is also essential to ensure transparency and buy-in for the results produced. On the other hand, this complexity should not prevent embarking on exploratory modelling exercises. Or, in the absence of data, the use of qualitative modelling approaches, such as the system mapping (CLD) presented in this document.

The following recommendations are provided for a correct integration of knowledge in the context of policy analysis for the estimation of health co-benefits.

- Concerning the conceptualization of the exercise, consider whether the analysis of health co-benefits is required to (i) complement an already available and detailed assessment, requiring solid information and high confidence in the results generated, or (ii) to shed light on new outcomes that have never been assessed, and for which a certain degree of uncertainty is acceptable. The former is often found in policy formulation assessments; the latter is more commonly found in policy evaluation assessment, which feed more directly in the policy decision-making process.
- In relation to data collection, first search for historical data or values selected from the existing literature or surveys, then test such data against existing models or published values. If adequate data are not available, consult experts to determine baseline assumptions that will allow for further calibration and validity testing. If the information collected is not sufficient, as a third step consider the use of simulation models to fill gaps in data.
- When developing assessments that integrate knowledge across policy domains, validate the data collected in relation to the literature in the field and also cross-check their consistency by comparing it with data from other sectors and fields (e.g. compare data on air pollution with data on energy consumption). This is important because errors in one sector could propagate to others, and there is far less data on the interconnections across sectors than for specific sectoral variables.
- Concerning model development and its validation, always perform direct structure tests to assess the validity of the model structure by direct comparison with knowledge about the structure of the real system. This involves assessing each relationship within the model individually and comparing it with available knowledge about the real system. Direct structure tests can be classified as empirical or theoretical. Empirical structure tests involve comparing the model structure with information (quantitative or qualitative) obtained directly from the real system being modelled. Theoretical structure tests involve comparing the model structure with generalized knowledge about the system, as characterized in the existing literature.
- When performing an economic valuation of health co-benefits, it is critical to have information and data on the driver of change (e.g. kg or tonnes of air pollutants emitted) and on the economic value of such driver (e.g. health cost of air pollution per tonne of pollutant emitted). These are the minimum input parameters and data required to proceed with and economic analysis. In the absence of such data, it is possible to consider the use of simulation models (e.g. for estimating energy consumption by energy source, to then estimate air pollutants) for replacing some of the data required. On the other hand, it is critical that any quantification (reaching beyond data and measurements) is carefully and thoroughly validated.

- In relation to data inputs used for the economic assessment, it is important to rely on local (or country-specific data). The use of information from other countries, sectors or sources not directly connected to the study area is likely to lead to imprecise results. For instance, when considering tree planting as the intervention option to analyse, it is important to know that the impact on flood mitigation, temperature mitigation and carbon sequestration varies considerably from one tree species to another. Local climatic conditions and soil characteristics have to be taken into account when assessing tree planting and hence when estimating the potential health co-benefits they may generate.
- Once the economic analysis is performed, it is important to assess the results generated in relation to the uncertainty that comes with the method utilized. It is therefore important to perform sensitivity analysis if input parameters have been used for which there is uncertainty. This assessment may also determine whether the results are solid enough, in case there is little evidence and empirical data to support the outcomes of the analysis (i.e. the wide range of possible numerical results that may emerge when carrying out sensitivity analysis).

The above are general recommendations that can be applied to the use of a variety of methods and models, and applied to the estimation of several types of health co-benefits. It is recommended that best practice is used to carry out sectoral assessments, and that the points above are taken into account especially for the integration of knowledge in a cross-sectoral assessment (e.g. when health co-benefits are added to a more conventional CBA for investments in energy, tree planting, resilience of buildings and health system operations, and more).

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Annex 1: Health impacts and their causes

Causes	Impacts	Reference
Air pollution	Respiratory diseases, cardiovascular damage, fatigue, headaches and anxiety, irritation of the eyes, nose and throat, damage to reproductive organs, nervous system damage.	*(27)*
	Cardiovascular diseases in development stages of infants and cancer later in life, as well as impact on cognitive performance.	*(29,30)*
Solid waste	High incidence of cancer and lymphoma has been found in populations living near contaminated sites and landfills (e.g. kidney, larynx, pancreas, liver, lung cancer) as well as higher risks for congenital malformations, low birth weight and neural tube defects. Other health problems concern noise, smell and issues due to annoyance, lowering the quality of life of affected residents.	*(34)*
Wastewater	Microorganisms in water can cause diarrhoea, skin and tissue infections and dysentery, while other disease-causing bacteria such as *E. coli* O157:H7, Salmonella, Vibrio and Leptospirosis can be found in untreated wastewaters.	*(41)*
Heatwaves	Exhaustion, cramps, syncope, strokes, kidney disorders, psychiatric illness, chronic pulmonary illness, diabetes and cerebrovascular accidents.	*(5)*
	Lost productivity, which will impact developing countries.	*(57)*
Vector-borne diseases	Modification of geographical range of the habitat of animal vectors of diseases such as malaria, dengue fever, chikungunya, yellow fever and the Zika virus.	*(51,52)*
Floods	Responsible for the emergence of waterborne diseases, as well as for the destruction of key infrastructure that in vulnerable areas can increase the displacement of refugees and dislocated people.	*(59,64)*
	Drowning, injuries and hypothermia, health risks are related to evacuation of patients, loss of health workers of health infrastructure such as essential drugs. Medium-term implications include infected wounds, poisoning, affected mental health, communicable diseases and starvation. In the long term, chronic diseases and poverty-related diseases such as malnutrition can impact severely on the affected population.	*(63)*
Droughts	Malnutrition and undernutrition	*(68,94)*
Extreme weather events	Deaths, physical injuries, mental health issues, water and food scarcity, water and vector-borne diseases, forced migration, and damage to health facilities.	*(71)*
Sea surface temperature	Fish stocks and fisheries production are decreasing, affecting the protein intake of many people. It is also affecting the nutritional values of the available seafood, leading to a reduction of lipids and proteins in some species.	*(72,78)*
Ozone depletion	Exposure to ultraviolet (UV) radiation leads to skin cancer, premature ageing of skin, signs of sun damage such as wrinkles, leathery skin and liver spots.	*(255,256)*
	Eye problems due to UV rays leading to the cornea becoming inflamed or burned, increased risk of cataracts	*(257)*
	Exposure to UV rays can also weaken the immune system, which leads to the body having a harder time fending off infections.	*(258)*

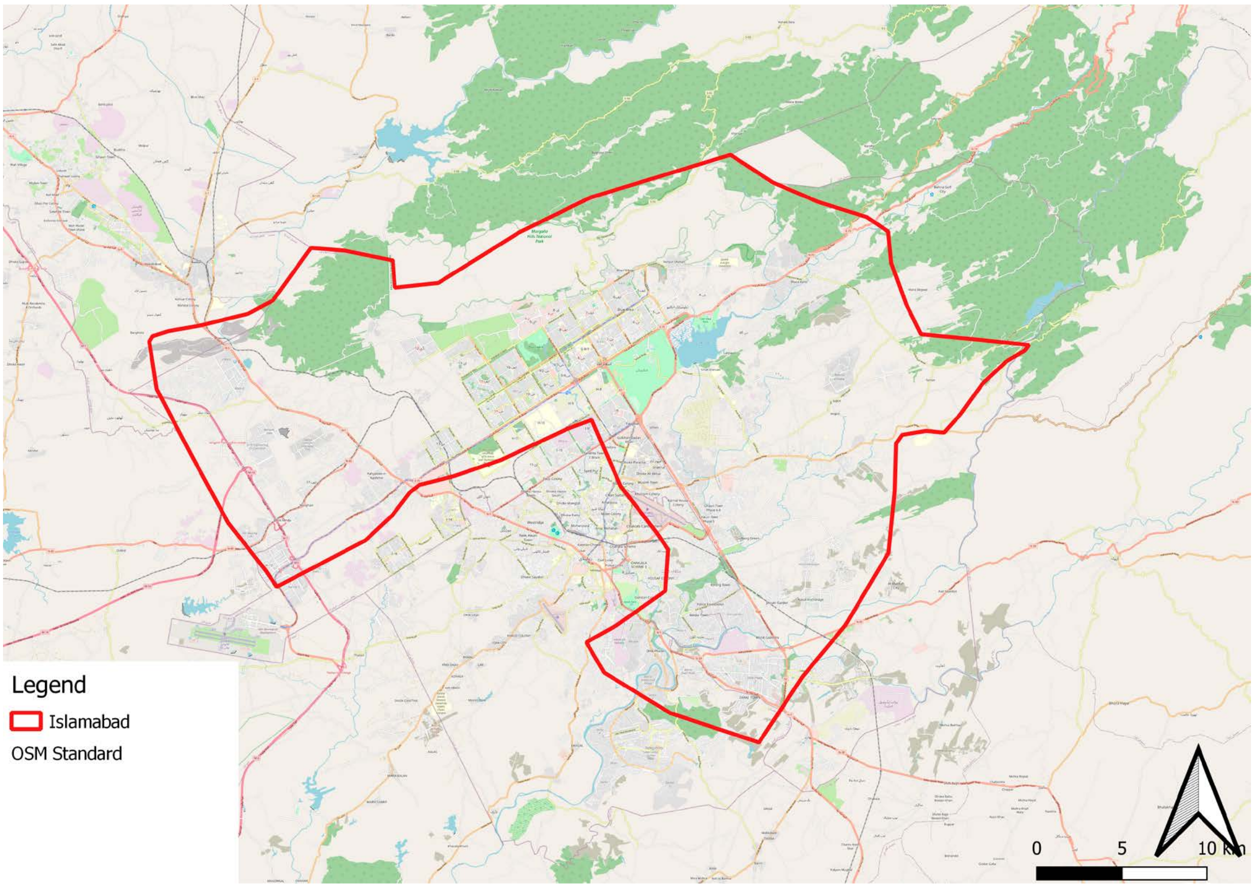
Annex 2: Economic valuation of health co-benefits of climate mitigation and adaptation – Pakistan case study

Method and study area

Study area

The study area of this analysis is Islamabad, the capital city of Pakistan (Fig. A2.1). We picked Islamabad as a simplified example for this case study. The same analysis can be conducted at the regional or country level, defining boundaries accordingly.

Fig. A2.1. Location of Islamabad, Pakistan



Coordinate system

We present the coordinate system used for the spatial simulations, to ensure that all relevant information of computational reproducibility is provided. Our analysis is based on the world project coordinate system called "V WGS 84 / Pseudo-Mercator – Spherical Mercator – ESPG: 3857". A geographical coordinate system uses a three-dimensional spherical surface to define locations on the earth (ESRI, s.d.). "EPSG:3857" is a projected coordinate system used in certain web mapping and visualization applications such as Google Maps and OpenStreetMap (espg.io, s.d.). A projected coordinate system uses global projected coordinates in metres for the entire planet.

Here is the detail of the coordinate system:

```
PROJCS["WGS 84 / Pseudo-Mercator",
  GEOGCS["WGS 84",
    DATUM["WGS _ 1984",
      SPHEROID["WGS 84",6378137,298.257223563,
       AUTHORITY["EPSG","7030"]],
      AUTHORITY["EPSG","6326"]],
    PRIMEM["Greenwich",0,
      AUTHORITY["EPSG","8901"]],
    UNIT["degree",0.0174532925199433,
         AUTHORITY["EPSG","9122"]],
       AUTHORITY["EPSG","4326"]],
PROJECTION["Mercator _ 1SP"],
PARAMETER["central _ meridian",0],
PARAMETER["scale _ factor",1],
PARAMETER["false _ easting",0],
PARAMETER["false _ northing",0],
UNIT["metre",1,
  AUTHORITY["EPSG","9001"]],
AXIS["X",EAST],
AXIS["Y",NORTH],
EXTENSION["PROJ4","+proj=merc +a=6378137 +b=6378137 +lat _ ts=0.0 +lon _ 0=0.0 +x _ 0=0.0
+y _ 0=0 +k=1.0 +units=m +nadgrids=@null +wktext +no _ defs"],
AUTHORITY["EPSG","3857"]]
```

Land cover maps

LULC BAU

The 2019 land-use/land-cover (LULC) map developed by the Copernicus Global Land Service at 100 m resolution *(1)* was used as LULC business-as-usual (BAU) map.

Fig. A2.2 shows the LULC map in the BAU scenario, while Fig. A2.3 shows the colour legend of each land class. We observe that most of the surface corresponds to cropland (pink), urban areas (red) and forests (green) as well as some herbaceous areas (yellow).

Fig. A2.2. Land-use/land-cover (LULC) map in business-as-usual (BAU) scenario

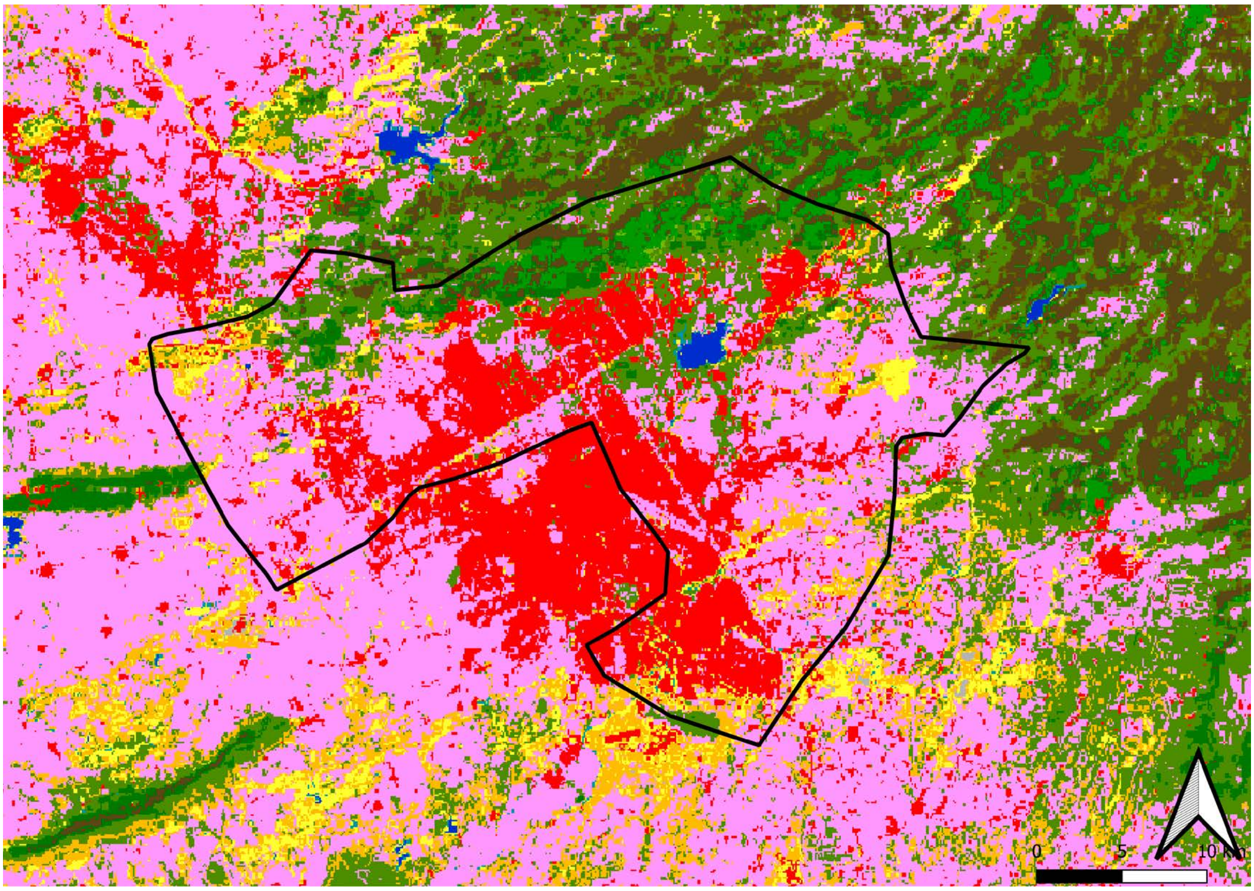
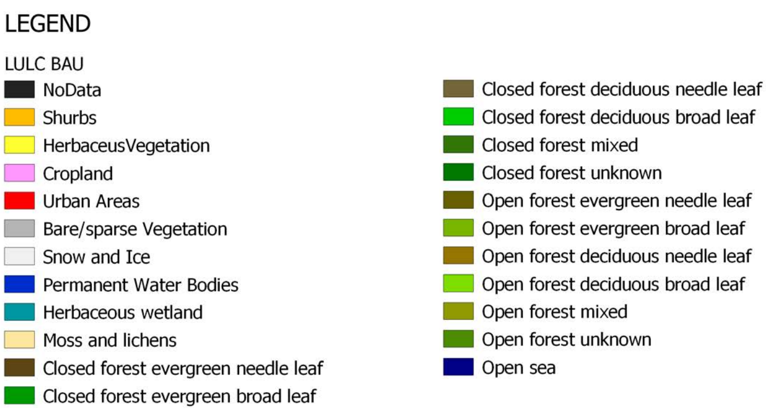


Fig. A2.3. Legend and codes (BAU)

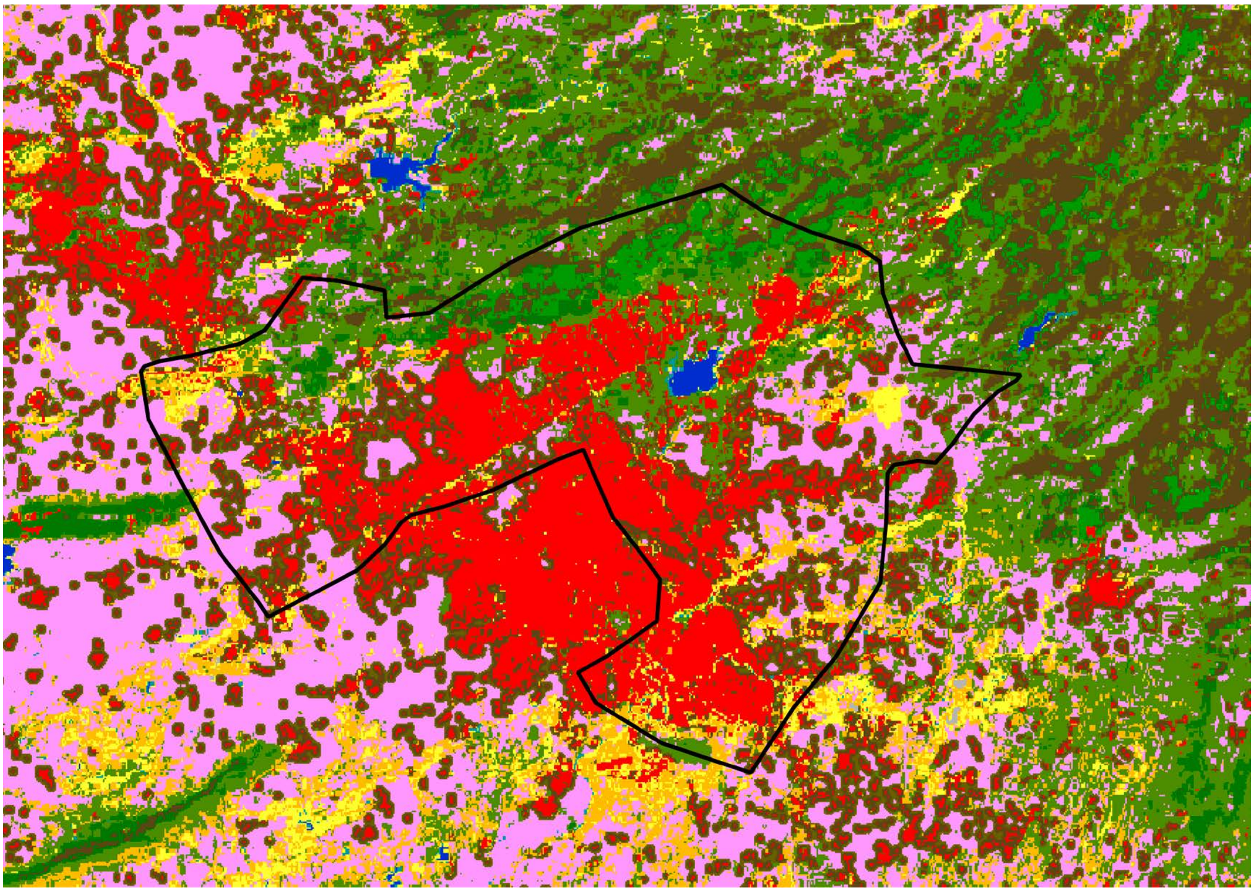


LULC trees outside Islamabad

Following the initiative "Billion Tree Tsunami" which consisted of planting one billion trees (restoring 350 000 ha) in the province of Khyber Pakhtunkhwa, the government of Pakistan aims to plant 10 billion trees in the coming years across the country *(2,3)*. We assumed that if 10 billion trees will be planted in the whole country, then 3 500 000 ha of land will be restored.

Using the InVEST Proximity Tool[a] and the 2019 LULC BAU map of the entire country as a reference, we converted 3 500 000 ha of cropland and bare land into tree cover, placing the new trees around urban areas. Fig. A2.4 shows the modelled LULC map with the new trees outside Islamabad, following the plantation of 10 billion trees in Pakistan. This map was used in the Urban Flood Risk model as an alternative to the LULC BAU map. In total, 30 645 ha of planted trees have been added to the map in Fig. A2.4 (within the boundaries of Islamabad). The planted trees represent 0.88% of the total area of Pakistan that will be reforested under the 10 billion trees initiative. These new hectares of planted trees have been placed outside the city because those locations are the most effective in reducing water flow and volume (via water retention) and water speed in case of flooding.

Fig. A2.4. LULC trees outside Islamabad



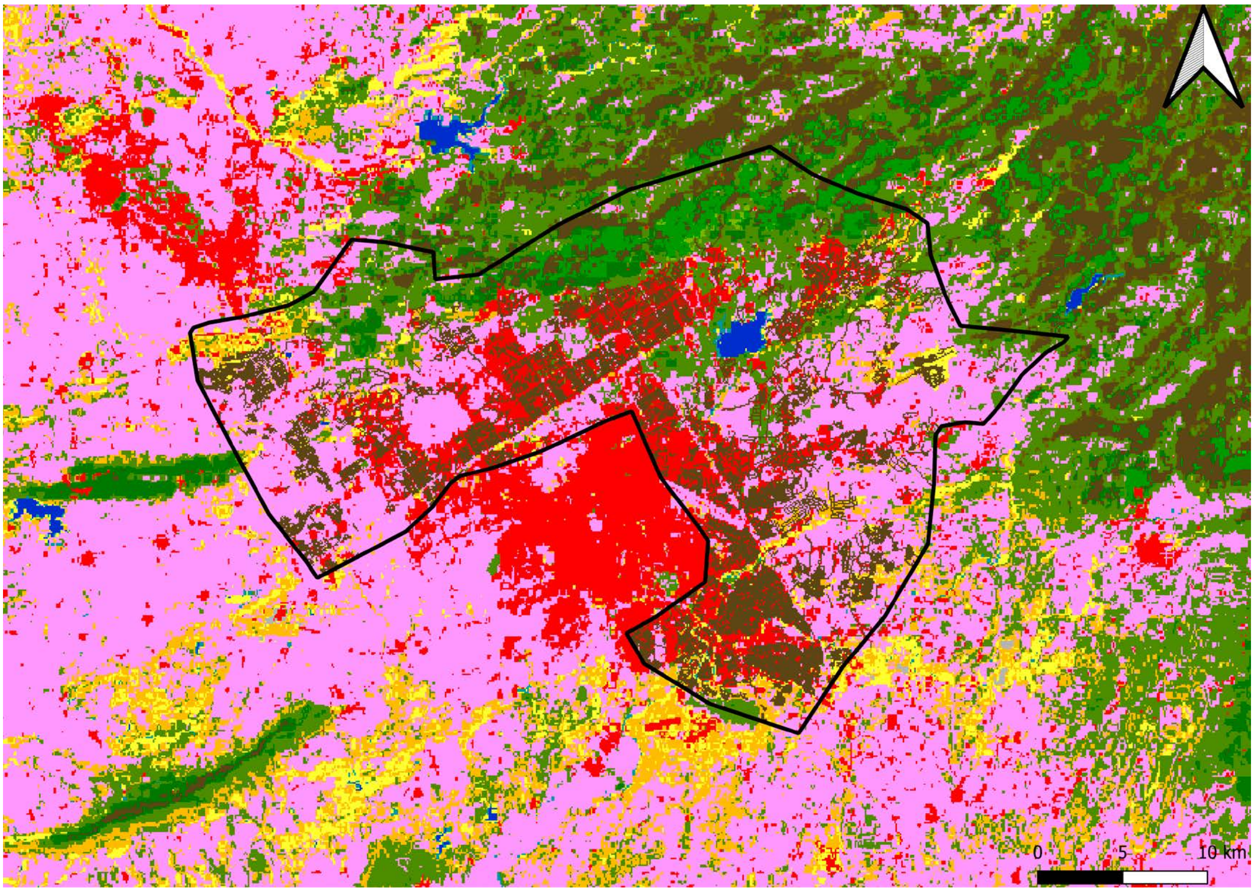
LULC trees on the residential roads of Islamabad

When we analyse the cooling effect of trees, we have to locate trees in urban areas, where people reside (e.g. along streets). This is where the cooling effect of trees is more relevant for the local population, as opposed to planting trees in agricultural areas or where population density is less. Therefore, we placed the new trees in correspondence of roads using the 2019 LULC map of Islamabad. Fig. A2.5 shows the new LULC map, which was used in the Urban Cooling Model. In total, 30 481 ha of planted trees have been

[a] https://invest-userguide.readthedocs.io/en/3.8.9/scenario_gen_proximity.html

added to the map in Fig. A2.5 (within the boundaries of Islamabad). The area of planted trees represents 0.87% of the total area in Pakistan that will be reforested under the 10 billion trees initiative.

Fig. A2.5. LULC trees over the roads of Islamabad



Software and simulation

The ecosystem services map simulation has been performed using InVEST Software V.3.9.0 (https://naturalcapitalproject.stanford.edu/invest/). The inputs spatial data for the InVEST model have been prepared by using QGIS-OSGeoW-3.4.2–1 (qgis.org/downloads/). The tabulated data are managed and prepared in Microsoft Excel V. 2016.

The outputs of the InVEST software are then used to estimate the monetary and health impacts using different references, as described in sections 1.2 and 1.3.

Urban flood risk

"Flood hazard comes from different sources, including: riverine (or fluvial) flooding, coastal flooding, and stormwater (or urban) flooding – the focus of this InVEST model. Natural infrastructure can play a role for each of these flood hazards. Related to stormwater flooding, natural infrastructure operates mainly by reducing runoff production, slowing surface flows, and creating space for water (in floodplains or basins).

"The InVEST model calculates the runoff reduction, i.e. the amount of runoff retained per pixel compared to the storm volume."[b]

Input data preparation and processing

Two LULC maps were used in this model, the ones described in section "Land cover maps". In other words, we considered two alternative LULC scenarios: the 2019 LULC (based on Islamabad's actual geography in 2019), and another one with the addition of trees, simulating trees placed around the city, replacing agricultural areas and bare areas (we assumed that those locations are the most vulnerable from the floods coming from outside the city).

For this analysis, we also used 200 mm as a rainfall reference since this value is indicated by Hashmi et al. *(4)* when severe floods hit the country in July 2010, just in four days. As a comparison, throughout July, normally 87 mm of precipitation is accumulated in Islamabad *(5)*.

InVEST results and monetary impacts

Fig. A2.6 and Fig. A2.7 show the runoff retention volumes (m^3) in the study area using both the LULC BAU and LULC trees maps, respectively. The darker the colour (black, violet), the lesser is the runoff retention.

[b] http://releases.naturalcapitalproject.org/invest-userguide/latest/urban_flood_mitigation.html

Fig. A2.6. Runoff retention values (m³) – LULC BAU

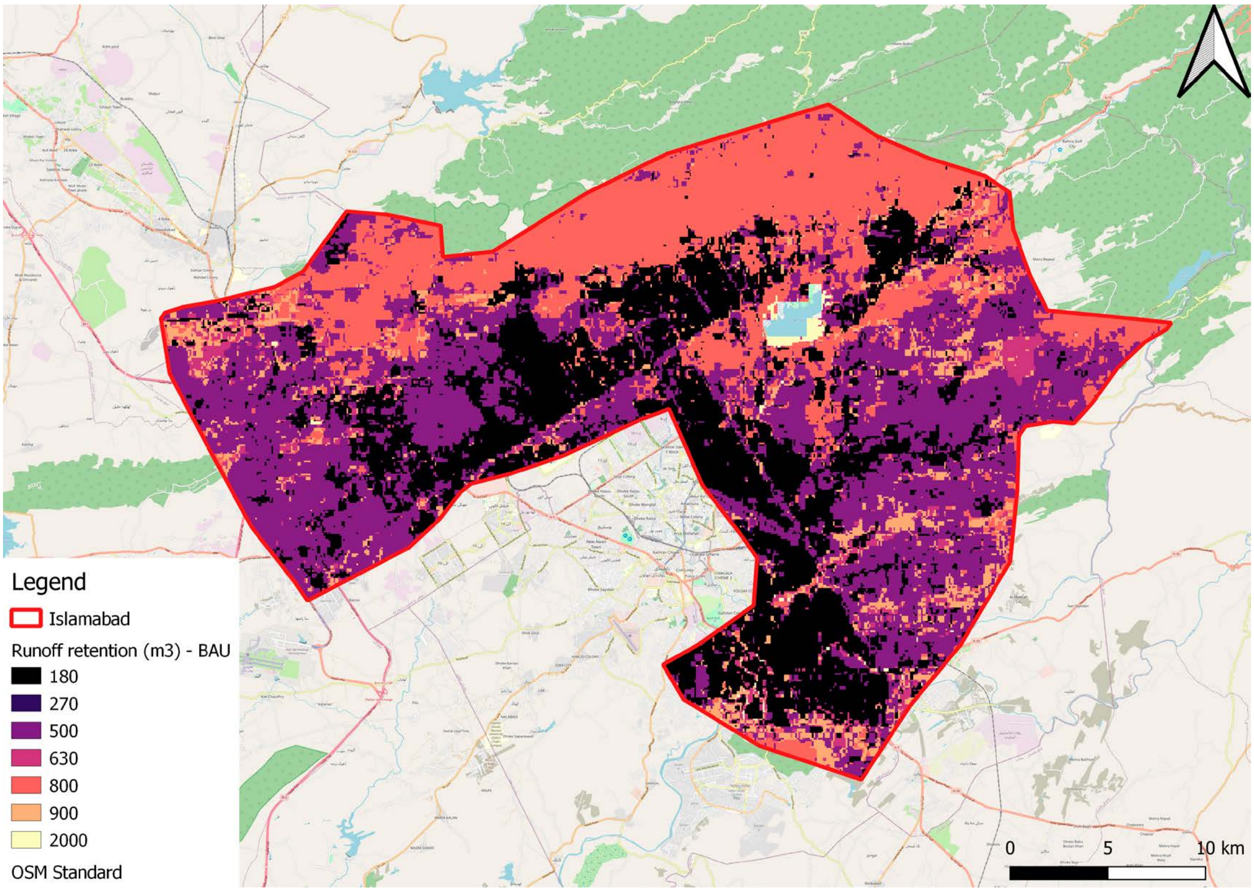


Fig. A2.7. Runoff retention values (m^3) – LULC trees

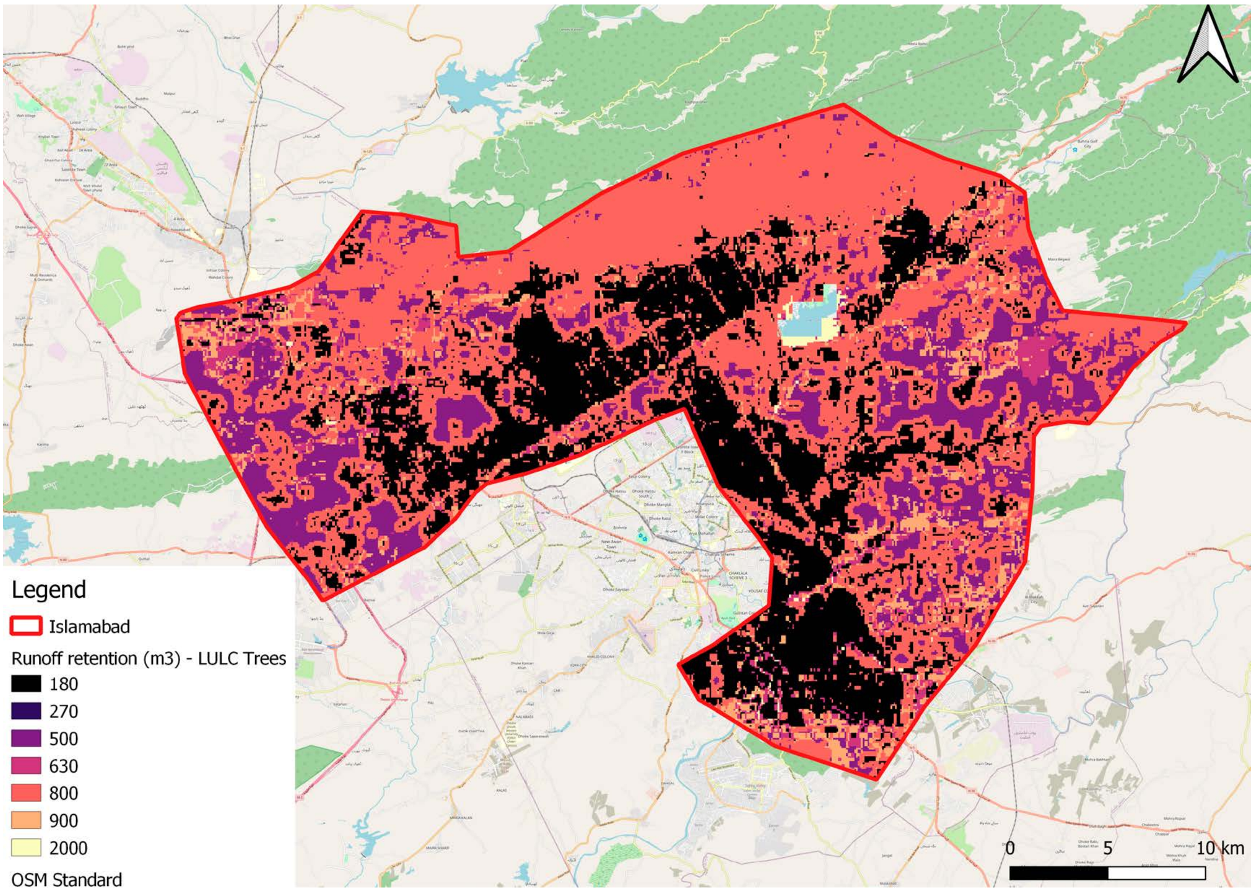
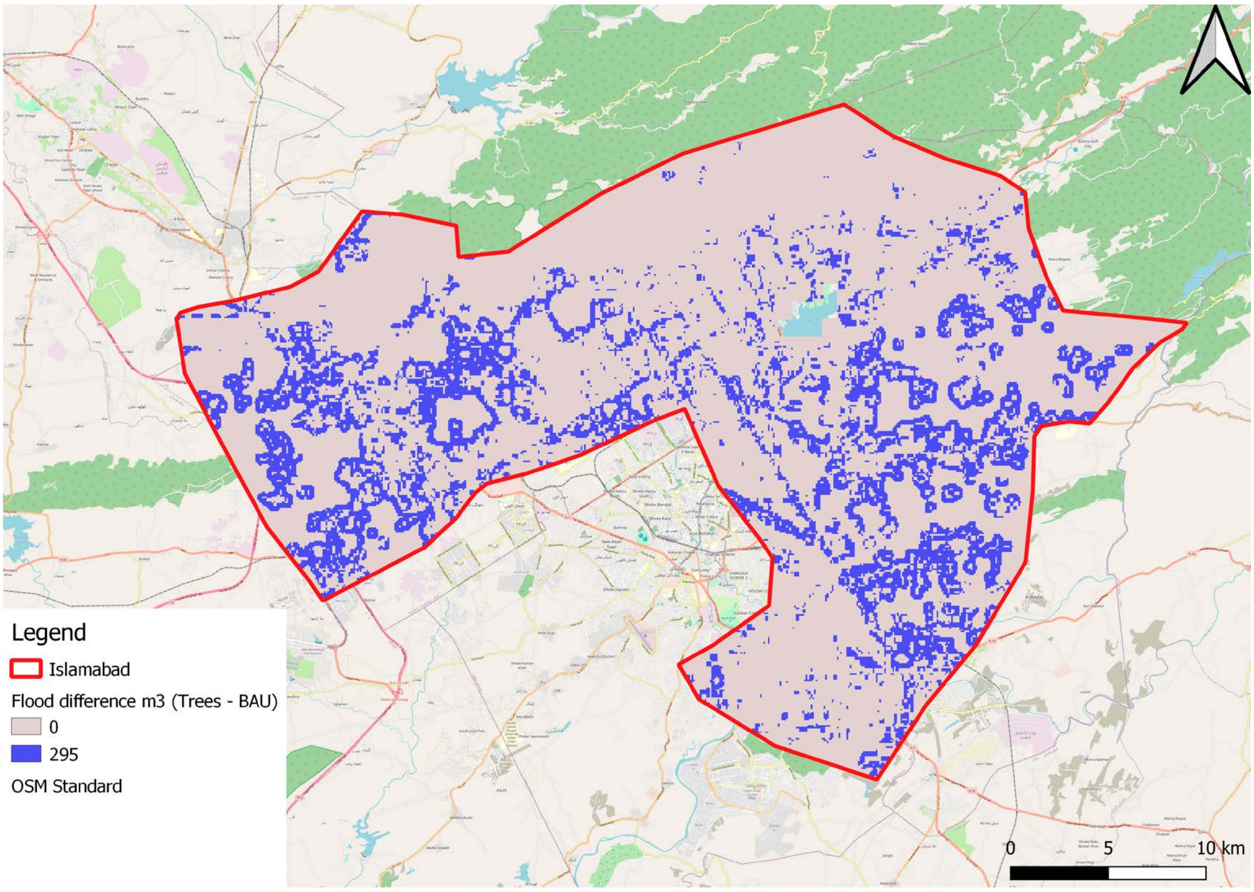


Table A2.1. Runoff retention statistics

LULC scenario	Total runoff retention volume (m^3)	Difference between LULC trees and LULC BAU (%)
LULC BAU	64 252 934.72	12.30
LULC trees	72 158 136.63	

As Table A2.1 shows, the total runoff retention volume would increase by more than 12% from the current landscape (LULC BAU) to the one where trees are planted outside the city (LULC trees), which means that in a rainfall event of 200 mm the landscape of Islamabad could retain almost 7.9 million m^3 more of rainfall. Fig. A2.8 shows the areas where water retention will increase (difference between planting of trees and BAU scenario).

Fig. A2.8. Areas where flood retention will increase (in blue – difference between planting of trees and BAU scenario)



As for the monetary impacts, we started from a 2018 report of the World Food Programme (WFP) indicating the economic impacts, in US$ millions, of major floods in Pakistan from 1950 to 2012 *(6)*. Considering that Islamabad accounts for 0.5% of the total population of the country, we multiplied the economic impacts indicated by the WFP by 0.5% to estimate the negative monetary consequences of floods in the capital city. The amount could be larger, considering the higher density of infrastructure in Islamabad, an urban area, compared with the rest of the country. Table A2.2 shows the economic impacts of flooding to infrastructure in Pakistan and in Islamabad from 1950 to 2012.

Table A2.2. Economic impacts of flooding in Pakistan and in Islamabad

Damage and loss caused by floods in Pakistan, 1950–2012		
Year	Direct loss (US$ million) – Pakistan	Direct loss (US$ million) – Islamabad (estimated)
1950	488	2.44
1955	378	1.89
1956	318	1.59
1957	301	1.505
1959	234	1.17
1973	5 134	25.67
1975	684	3.42
1976	3 485	17.425
1977	338	1.69
1978	2 227	11.135
1981	299	1.495
1983	135	0.675
1984	75	0.375
1988	858	4.29
1992	3 010	15.05
1994	843	4.215
1995	376	1.88
2010	10 000	50
2011	3 730	18.65
2012	2 640	13.2

Considering the average economic impacts of flooding in Islamabad from 1992 to 2012 (US$ 17.2 million), we can assume that if tree planting efforts can increase water retention by 12.30%, then the average economic impacts of flooding during those years can be reduced by the same share, which would correspond to US$ 2.11 million annually. If we assume that the average lifetime of trees is 30 years, then the total avoided costs would amount to US$ 63.34 million up to 2050.

If we assume that the 2010 event (the one that had a rainfall of 200 mm, base used for the modelling exercise), which produced an estimated cost of US$ 50 million in Islamabad, will occur every 10 years over the next 30 years, then the avoided economic costs from extreme events would amount to US$ 18.45 million.

Concerning the investment for tree planting in Islamabad, as argued in section "Land cover maps", we assumed that if 10 billion trees will be planted in Pakistan, then 3 500 000 ha will be restored. It has been estimated that the project, at the national level, will cost US$ 750 million *(7)*. Therefore, the cost per hectare will be roughly US$ 215. Starting from this information, we scaled down the costs for the new area of planted trees in Islamabad (30 645 ha). The total investment for tree planting in Islamabad is slightly more than US$ 6.5 million, since we "planted" 30 645 ha of trees.

Table A2.3 shows the avoided costs from flooding in two scenarios: considering the constant annual impacts of flooding over the next 30 years and considering that three events similar to the 2010 flooding will occur during the same period. Both scenarios show that the investment in tree planting will substantially reduce losses and will largely compensate costs.

Table A2.3. Avoided economic costs of flood impacts on infrastructure with tree planting (30 years)

	Investment over a 30-year period
Avoided costs from regular flooding	US$ 39 110 310
Avoided costs from extreme events	US$ 18 450 000
Total avoided cost	US$ 57 560 310
Investment for tree planting in Islamabad	US$ 6 566 786
Savings	US$ 50 993 524

Concerning cost-effectiveness of tree planting in Islamabad, Table A2.3 shows that the total cumulative savings in 30 years, considering constant annual impacts of flooding and also considering that the 2010 flooding event will occur three times, will amount to US$ 50 993 524. We estimated that the investment for tree planting in Islamabad will amount to US$ 6 566 786. This means that for every US$ 1 invested in tree planting, benefits of US$ 7.77 will be generated.

Concerning the lives lost, we stated from a report of the WFP indicating the total deaths, of major floods in Pakistan from 1950 to 2012 *(6)*. Considering that Islamabad accounts for 0.5% of the total population, we multiplied the number of lives lost indicated by the WFP by 0.5% to estimate the number of total deaths from floods in the capital city. The number could be larger, considering the higher population density of Islamabad, an urban area, compared with the rest of the country. Table A2.4 shows the lives lost due to flooding in Pakistan and in Islamabad from 1950 to 2012.

Table A2.4. Lives lost in Pakistan and in Islamabad due to flooding

Damage and loss caused by floods in Pakistan, 1950–2012		
Year	Lives lost (number) – Pakistan	Lives lost (number) – Islamabad (estimated)
1950	2 190	10.95
1955	679	3.40
1956	160	0.80
1957	83	0.42
1959	88	0.44
1973	474	2.37
1975	126	0.63
1976	425	2.13
1977	848	4.24
1978	393	1.97
1981	82	0.41
1983	39	0.20
1984	42	0.21
1988	508	2.54
1992	1 008	5.04
1994	431	2.16
1995	591	2.96
2010	1 985	9.93
2011	516	2.58
2012	571	2.86

Considering the average deaths due to flooding in Islamabad from 1992 to 2012 (4.25), we can assume that if tree planting efforts can increase water retention by 12.30%, then the average lives lost due to flooding during those years can be reduced by the same share, which would correspond to 0.52 lives annually. If we assume that the average lifetime of trees is 30 years, then the total avoided deaths would be 15.7 up to 2050. Further health-related impacts have not been included, which means that the health co-benefits are larger.

If we consider the 2010 flood event, the disaster affected more than 20 million people in Pakistan (impacts include destroyed homes and malnutrition) *(8)*. Considering that Islamabad accounts for 0.5% of the total population, we multiplied the number of people affected in the country by 0.5% to estimate the total number of people affected from the 2010 flood event in the capital city: 100 000. If we assume that tree planting efforts can increase water retention by 12.30%, and that that the number of people affected can be reduced by the same share, then 12 300 people would be saved from the negative consequences of a similar flooding event like the one in 2010, at least in the capital city. Considering the investment for tree planting in Islamabad (US$ 6 566 786), and the estimated number of people that will avoid the negative consequences of flooding (12 300), we can estimate that the cost of avoiding the impact of flooding would amount to approximately US$ 534 per person.

Urban cooling

Vegetation can help reduce the urban heat island (UHI) effect by providing shade, modifying thermal properties of the urban fabric, and increasing cooling through evapotranspiration. This has consequences for the health and well-being of citizens through reduced mortality and morbidity, increased comfort and productivity, and the reduced need for air conditioning (A/C). The InVEST Urban Cooling Model calculates an index of heat mitigation based on shade, evapotranspiration, and albedo, as well as distance from cooling islands (e.g. parks). The index is used to estimate a temperature reduction by vegetation.[c]

Input data preparation and processing

Two LULC maps were used in this model, the ones described in in section "Land cover maps". In other words, we considered two alternative LULC scenarios: the 2019 BAU scenario, and another one with trees planted along the streets of the city, since we consider that trees can reduce the urban heat island effect the most if placed in the city.

We used 31 °C as average temperature in Islamabad in June,[d] and we also considered in the model an increase of 5.24 °C, since this is the maximum estimated rise in temperatures in Pakistan *(9)*. We used 31 °C as a reference value for the temperature in Islamabad with no increase in temperatures.

InVEST results and monetary impacts

The following is a short description of the most important outputs from the Urban Cooling Model.

1. **uhi_results_[Suffix].shp:** A copy of the input vector with areas of interest with the following additional fields:
    - "avg_tmp_v" – Average temperature value (degrees centigrade [°C])
2. **hm_[Suffix].tif:** The calculated heat mitigation index maps (spatial outputs)

The first outputs "uhi_results" are simple vectors and do not show any relevant spatial outputs. However, they indicate the "average temperature value (°C)" using the LULC BAU and LULC trees maps. These average temperature values show the average temperatures in the whole study area considering the reference temperatures of 31 °C and the increase in temperatures of 5.24 °C, as well as the cooling effect of the landscape. It should be noted that the average temperature values using the LULC BAU map are not 36.24 °C (31+5.24) because the model considers the cooling effect of the landscape (such as from existing vegetation). Table A2.5 shows the average temperature using the two LULC maps.

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[c] http://releases.naturalcapitalproject.org/invest-userguide/latest/urban_flood_mitigation.html

[d] https://www.holiday-weather.com/islamabad/averages/june/

Table A2.5. Urban cooling statistics

LULC scenario	Average temperature value (°C)	Difference between LULC trees and LULC BAU (°C)
LULC BAU	34.3	-0.7
LULC trees	33.6	

As Table A2.5 shows, the average temperature value in Islamabad is 0.7 °C higher using the LULC BAU map compared to the outputs using the LULC trees maps. In other words, planting trees on the streets of Islamabad can potentially reduce the average temperatures.

Fig. A2.9 and Fig. A2.10 show calculated heat mitigation index maps using the LULC BAU and LULC trees maps, respectively. They can be useful to understand the locations where the cooling effects of trees will be more relevant. The bluer the zones, the higher is the cooling effect.

Fig. A2.9. Heat mitigation index (LULC BAU)

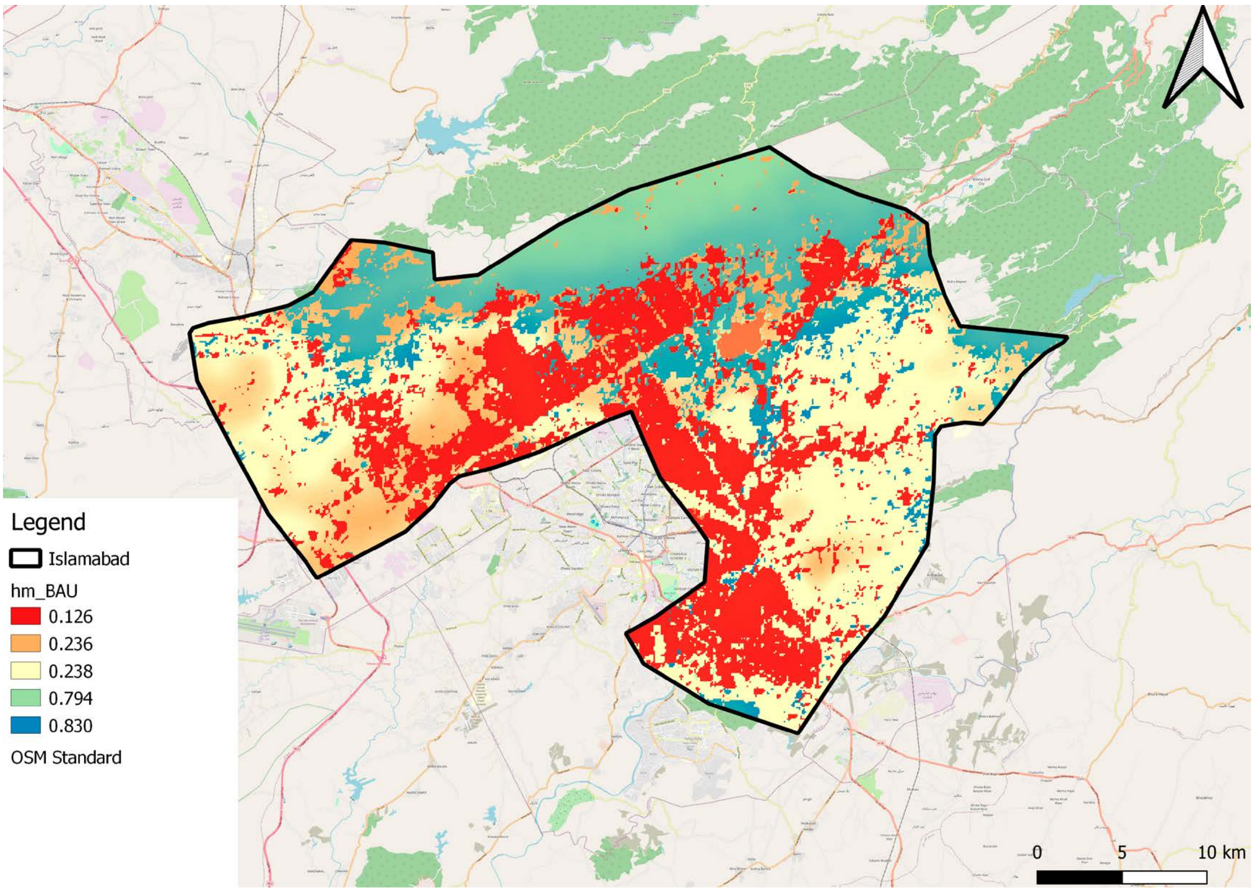
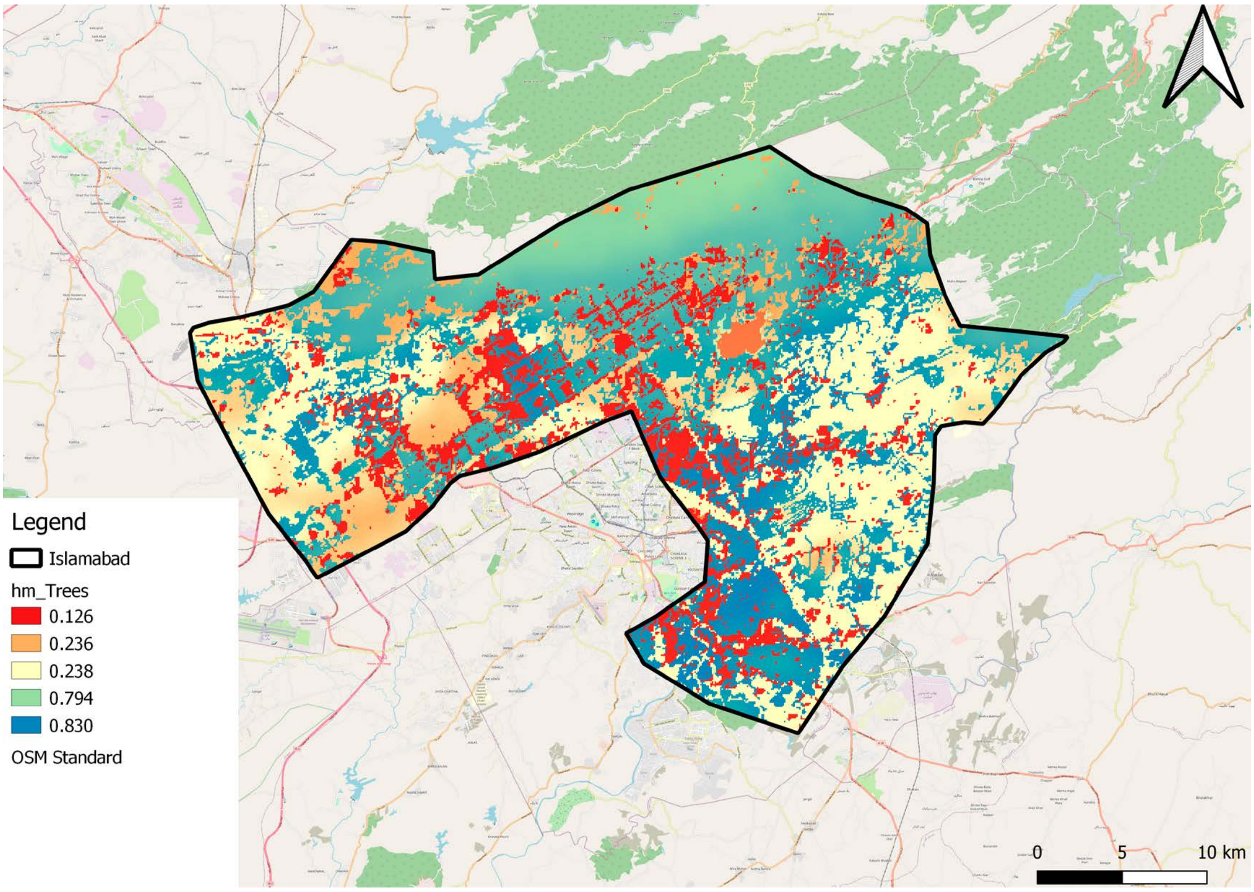


Fig. A2.10. Heat mitigation index (LULC trees)



Concerning economic impacts of temperature mitigation, the Government of Pakistan *(10)* indicated that a 1 °C increase in temperatures leads to a 4.6% increase in cases of diarrhoea, also providing the estimated annual economic costs of climate change in Pakistan on temperature-related diarrhoea. If we assume that our InVEST results, which indicate that thanks to reforestation efforts it is possible to avoid 0.7 °C of local warming, we can calculate the avoided costs of temperature-related diarrhoea since we will be able to avoid a 3.22% (70% of 4.6%) increase in cases of diarrhoea.

Table A2.6 provides an economic analysis starting from the baseline costs (lower and higher bounds) of temperature-related diarrhoea provided by the Government of Pakistan *(10)* (these costs include treatment costs, transportation costs, non-health costs, days of school absenteeism, productive parent-days lost, and deaths related to diarrhoea). Table A2.6 also shows the expected annual cost reduction due to tree planting, as well as the total annual costs in 2050 in the absence of tree planting (assuming that the average temperatures will increase by 0.7 °C in the medium-to-long term from the baseline). Finally, Table A2.6 also shows the cumulative cost reduction due to tree planting in Pakistan.

Table A2.6. Cumulative cost reduction due to tree planting

	Baseline – economic costs of temperature-related diarrhoea	Total annual costs in 2050 in the absence of tree planting	Expected annual cost reduction due to tree planting	Cumulative cost reduction due to tree planting by 2050
Temperature-related diarrhoea – Lower bound	US$ 122 530000	US$ 126 475 466	US$ 3 945 466	US$ 57 209 257
Temperature-related diarrhoea – Upper bound	US$ 316 550 000	US$ 326 742 910	US$ 10 192 910	US$ 147 797 195

Table A2.7 provides an economic analysis starting from the cumulative cost reduction due to tree planting in Pakistan shown in the fifth column of Table A2.6. We divided that result by 220 900 000, which is equivalent to the total population of the country. In this way, we obtained the cumulative cost reduction due to tree planting per person. We then multiplied that result by 1 015 000, which is equivalent to the population of Islamabad to obtain the cumulative cost reduction due to tree planting in the capital.

Table A2.7 also shows the investment for tree planting in Islamabad. As indicated in section "Land cover maps", we assumed that if 10 billion trees will be planted in Pakistan, then 3 500 000 ha of land will be restored. It has been estimated that the project will cost US$ 750 million *(7)*. Therefore, the cost per hectare will be roughly US$ 215. The total investment for tree planting in Islamabad would be slightly more than US$ 6.5 million, since we "planted" 30 481 ha of trees.

As Table A2.7 shows, the savings (cumulative cost reduction – cost of tree planting) in Islamabad are negative. However, we considered the cost reduction due to tree planting only for reducing the costs of temperature-related diarrhoea. Examples of additional outcomes from urban trees that were not considered include reduction in air pollution, water filtration, improvement of mental health, and improvement of labour productivity due to the cooling effect *(11,12)*. These would add to the co-benefits creating additional savings.

The goal of this analysis is to add the health dimension to investments that would be done for other purposes. Therefore, our results proved that considering the health dimension in tree planting initiative led to a reduction of costs.

Table A2.7. Avoided economic costs of temperature-related diarrhoea with tree planting

	Cumulative cost reduction due to tree planting (per person)	Cumulative cost reduction due to tree planting (whole population of Islamabad)
Temperature-related diarrhoea – Lower bound	US$ 0.26	**US$ 262 867**
Temperature-related diarrhoea – Upper bound	US$ 0.67	**US$ 679 104**
Investment for tree planting in Islamabad		**US$ 6 531 643**
Savings – Lower bound		**US$ (6 268 776)**
Savings – Upper bound		**US$ (5 852 538)**

Considering the potential avoided cases of temperature-related diarrhoea, we started from a study *(13)* which indicated that in the Sindh province (population: 47.9 million people), over 150 000 cases of diarrhoea were reported in 2014, which is equivalent to 0.0031 cases per person. The population of Islamabad is approximately 1 015 000 people, and if we assume that in the capital there are 0.0031 cases of diarrhoea per person, then 3178.5 people are impacted by that disease each year.

In our study, we concluded that reforestation efforts in Islamabad may avoid an increase of 3.22% in the cases of diarrhoea in the capital city, which would correspond to 102.35 cases annually. If we consider that the average lifetime of trees is 30 years, then the reforestation project would avoid 3070.43 cases of diarrhoea. Considering the capital investment for tree planting in Islamabad (US$ 6 531 643), we can conclude that US$ 2127.27 are needed to avoid a single case of diarrhoea in the capital city. Nevertheless, the benefits may be higher in more densely populated areas.

Agriculture (climate-smart agriculture)

System of rice intensification (SRI)

It is expected that by 2040 assuming a 0.5 °C increase in average nationwide temperatures, an 8–10% loss is expected across all crops *(14)*. We considered an average decline of 9%.

From FAOSTAT[e] we retrieved the total area of rice cultivated in Pakistan in 2018, as well as the tonnes produced in the same year (2 810 030 ha and 10 802 949 tonnes, respectively).

If we consider that a 0.5 °C increase leads to a crop decline of 9%, in Pakistan 972 265 tonnes of rice would be lost. Therefore, the rice production in this scenario will be 9 830 684 tonnes. Considering the producer prices (US$ 192.8 per tonne), retrieved from FAOSTAT, a decline of 972 265 tonnes of rice would correspond to US$ 187 452 771 of lost revenue.

The system of rice intensification (SRI) is a climate-smart agriculture (CSA) practice that increases the productivity of irrigated rice by modifying the management of nutrients, plants, soil and water (for example, by applying water intermittently, by using integrated pest management rather than herbicides, or by spacing rice seedlings farther apart on a regular grid rather than randomly) *(15,16)*.

It has been estimated that SRI increases yield by 43% on average *(17)*. Considering the decline of 9% due to climate change, the land productivity, measured in tonnes/ha of cultivated rice in Pakistan would decrease from the current value of 3.84 tonnes/ha to 3.49 tonnes/ha. If the impact of SRI is also considered, then the land productivity would increase to 5.15 tonnes/ha. Thus, considering the current land productivity (3.84 tonnes/ha) and the one expected with climate change impacts under SRI production (5.15 tonnes/ha), the area of land required to avoid loss of production and revenue comes to 746 115 ha of land cultivated with SRI practices.

The capital cost of implementing SRI amounts to 52 Franc CFA per kg of rice *(18)*. This value corresponds to US$ 90 per tonne, which multiplied by 972 265 (tonnes of rice that would be lost considering a 0.5 °C increase) is equal to US$ 87 503 850. This is the capital cost of SRI in this macroanalysis. Table A2.8 shows the net benefit emerging from using SRI.

Table A2.8. Savings from SRI, considering exclusively crop production

Capital cost of SRI	US$ 87 503 850
Avoided costs	US$ 187 452 692
Net benefit	US$ 99 948 842

e https://www.fao.org/faostat/en/#data

As Table A2.8 shows, the benefit-to-cost ratio (BCR) of the intervention is 2.14. The BCR was calculated by dividing the avoided costs by the capital costs.

It is worth noting that another reference indicated that SRI reduces production costs by 24% *(17)*. The same reference indicates that SRI leads to an average increase of net income by 128% (59–412%). It is also important to highlight that the method proposed in this section was carried out at the macro level, without considering the importance of micronutrients. Studies at the local level should be carried out if data on nutrition, consumption and nutritional values of local crops are available. In other words, our method presents high variabilities and needs more accurate local data to generate more precise outputs.

Malnutrition is a widespread problem in Pakistan, where nearly a quarter of the population is not able to afford the nutritional requirements (2350 calories per day) of an adult *(19)*. This means that in a population of 220 900 000 people, 55 225 000 are malnourished.

The Government of Pakistan (2021a) indicated that the annual average economic cost of climate change in the country amounts to US$ 1.59 billion, and that one sixth of it is attributable to malnutrition (roughly US$ 265 million). In other words, considering that the total malnourished population of Pakistan is more than 55 million, the annual economic costs (in US$/person) amount to US$ 4.8. This information may be used to estimate the economic costs of local populations that are impacted by malnutrition. Other useful data include: the economic benefits per person (US$ 1.8) calculated from the net benefits divided by the number of malnourished people and the avoided cost per person (US$ 3.4) calculated from the total avoided costs divided by the number of malnourished people. Table A2.9 summarizes the estimated costs, benefits, and avoided costs of SRI in Pakistan.

Table A2.9. Estimated costs, benefits and avoided costs per person of SRI in Pakistan

Annual cost of malnutrition due to climate change	US$ 265 000 000
Number of malnourished people	55 000 000
Annual cost of malnutrition per person	**US$ 4.8**
Net benefits of SRI	US$ 99 948 842
Number of malnourished people	55 000 000
Economic benefits of SRI per person	**US$ 1.8**
Total avoided cost of SRI	US$ 187 452 692
Number of malnourished people	55 000 000
Avoided cost of SRI per person	**US$ 3.4**

Finally, regarding the impact on nutrition of SRI, we considered the food composition table provided by Lukmanji et al. *(20)*, which gives the nutritional composition of rice. Table A2.10 shows some of the nutritional values of rice (per 100 g) as well as the total nutritional values of 972 265 tonnes of rice (the ones that will be produced through SRI). Table A2.10 also shows the added daily nutritional values per malnourished person (55 million).

Table A2.10. Nutritional values of rice

Rice, white, grain, raw[f]	ENERGY_KC	PROCNT	FAT	CHOCDF	FASAT	FAMS	FAPU	SUCS
100 g	358	6.5	0.5	79.8	0.1	0.2	0.1	0.3
972 265 tonnes	3500 billion	63 billion	4.9 billion	780 billion	970 million	1.9 billion	970 million	2.9 billion
Additional daily nutritional values per person	173.39	3.15	0.24	38.65	0.05	0.10	0.05	0.15

[f] ENERC_KCAL: energy in kilocalories
PROCNT: total protein in grams
FAT: total fat in grams
CHOCDF: total carbohydrates by difference in grams
FASAT: saturated fatty acids in grams
FAMS: monounsaturated fatty acids in grams
FAPU: polyunsaturated fatty acids in grams
SUCS: total sugar in grams

Vector-borne diseases (building resilience)

According to White et al. (2011), the global average economic cost of treating one person per year due to vector control diseases amounts to US$ 49.62. The Directorate of Malaria Control (DMC) of Pakistan indicated that the cases of malaria in the country are 3.5 million every year.

Screened ceilings are a vector control measure that allows lowering the number of mosquitoes in houses by 47% *(21)*. Thus, if we assume that such a decline corresponds to a decrease in malaria infections, the avoided economic costs of malaria in Pakistan would amount to US$ 81 624 900 per year. Considering that Islamabad accounts for 0.5% of the total population, the avoided costs in the capital city would amount to US$ 375 053 per year.

The economic cost of screened ceilings amounts to US$ 10 per person *(21)*. Starting from this information, we assumed every family in Pakistan is composed of 5.45 people (the fertility rate is estimated to be 3.45 according to the World Bank (2019) *(22)* and we also considered two parents). Therefore, the capital costs would amount to US$ 405 321 101 at the country level (population 220 900 000) and to US$ 1 862 385 for Islamabad (population 1 015 000).

Screened ceilings also allow cutting energy costs by 10% (lower estimate *(23)*). It has been estimated that a 10% electricity savings in buildings and homes in Pakistan could result in an overall savings of approximately 1200–1500 MW per day, which corresponds to an average annual saving of 492 750 MW or 492 750 000 kWh *(24)*. Considering that the electricity tariff in Pakistan is US$ 0.052 per kWh *(25)*, the avoided annual costs of electricity will amount to US$ 25 623 000 and to US$ 117 734 in Pakistan and in Islamabad, respectively.

To summarize, we expect that in Islamabad the capital costs of screened ceilings and the annual avoided costs of malaria and energy use will amount to US$ 1 862 385, US$ 117 734 and US$ 375 053, respectively. If we consider only annual costs and benefits, then the costs are much higher than avoided costs. However, assuming that the average lifetime of a screened ceiling is 20 years, then the total avoided costs would be 20 times larger, as shown in Table A2.11. In other words, over 20 years in Islamabad, investing US$ 1 in screened ceiling would allow to generate US$ 5.29 in avoided costs.

Table A2.11. Capital and avoided costs of screened ceiling

	1 year		20 years
	Pakistan	**Islamabad**	**Islamabad**
Screened ceiling cost	US$ 405 321 101	US$ 1 862 385	US$ 1 862 385
Avoided costs – electricity	US$ 25 623 000	US$ 117 734	US$ 2 354 671
Annual cases of malaria	3 500 000	16 082	321 639
Annual cost of malaria	US$ 173 670 000	US$ 797 986	US$ 15 959 715
Avoided cost of malaria with screening	US$ 81 624 900	US$ 375 053	US$ 7 501 066

Finally, if we consider that all the population of Islamabad will have to pay US$ 10 per person for screened ceiling, then the total economic cost will amount to US$ 10 150 000. Considering that over 20 years the total avoided cost in the capital city will amount to US$ 9 855 737, it is possible to indicate that a break-even can be reached in approximately two decades from the investment.

In both cases, additional cost savings due to reduced number of malaria cases are not considered, but would add to the equation favouring the investment in screened ceilings.

Emissions from energy – morbidity

The U.S. Environmental Protection Agency (2013) provided monetary values (US$) (mortality and morbidity) per tonne of directly emitted PM2.5 reduced in 2020 from the electricity sector *(26)*. The study used two different references to estimate the mortality and morbidity costs. The discount rate was set at 7%.

Table A2.12. Monetary values (US$) (mortality and morbidity) per tonne of directly emitted PM2.5 reduced in 2020 from the electricity sector

	Directly emitted PM2.5
	7% discount rate
Krewski et al. (2009) *(27)*	US$ 120 000
Lepeule et al. (2012) *(28)*	US$ 280 000

Studies that have valued both mortality and morbidity from ambient PM2.5 pollution indicated that the health costs of morbidity are generally 10–20% of the cost estimate that includes both morbidity and mortality *(29)* (Enriquez, Larsen, & Sánchez-Triana, 2018). Therefore, using the lower bound (10%) we multiplied the values shown in Table A2.12 by 10% to obtain the morbidity cost per tonne of directly emitted PM2.5 reduced in 2020 from the electricity sector.

Next, we calculated the total PM2.5 emissions from energy consumption and power generation in Pakistan under different scenarios, as shown in Table A2.13. We also calculated the difference in emission within each scenario between 2030–2020 and 2050–2020.

Table A2.13. Total PM2.5 emissions from energy consumption and power generation

Scenario/ pollutant	Unit	2020	2030	2050	Difference 2030–2020	Difference 2050–2020
NDC reference	Tonne/year	664 847	805 248	949 134	*140 401*	*284 287*
Business as usual (BAU)	Tonne/year	664 847	763 467	797 905	*98 620*	*133 058*
Current ambition	Tonne/year	664 847	708 416	562 111	*43 569*	*-102 736*
High ambition	Tonne/year	664 847	621 095	337 961	*-43 752*	*-326 886*

By multiplying the cost (US$) per tonne of directly emitted PM2.5 reduced in 2020 from the electricity sector (Table A2.12), by 10% which is the share of morbidity costs *(29)*, and by the difference in emissions within each scenario between 2030–2020 and 2050–2020 (Table A2.13), we were able to calculate the morbidity costs of emissions from the energy sector in Pakistan under different scenarios, as summarized in Table A2.14. It is worth noting that Table A2.14 considered the average costs of tonne of emitted PM2.5 shown in Table A2.12.

Table A2.14. Economic costs of PM2.5 emissions under different scenarios

Scenario/pollutant	Unit	Difference 2030–2020	Difference 2050–2020
NDC reference	US$	*2 808 020 000*	*5 685 740 000*
Business as usual (BAU)	US$	*1 972 400 000*	*2 661 160 000*
Current ambition	US$	*871 380 000*	*-2 054 720 000*
High ambition	US$	*-875 040 000*	*-6 537 720 000*

As Table A2.14 indicates, between 2020 and 2030 the only scenario showing negative economic impacts on morbidity (thus, economic benefits, meaning that the emissions of PM2.5 have been reduced) is the high ambition scenario. The same occurs between 2020 and 2050, with the "current ambition" scenario also showing negative economic impacts on health.

In addition to the annual morbidity cost, we estimated the cumulative value of climate mitigation investments up to 2030 and 2050. Table A2.15 shows the cumulative economic benefits of PM2.5 emission reduction compared to the NDC reference scenario.

Table A2.15. Cumulative economic benefits of PM2.5 emission reduction from the baseline

Average economic benefits	2020–2030	2020–2050
Business as usual (BAU)	US$ 4 124 173 750	US$ 43 625 015 000
Current ambition	US$ 9 667 287 500	US$ 109 107 137 500
High ambition	US$ 18 974 901 250	US$ 184 008 721 250

When adding avoided costs for morbidity and mortality, with the latter being obtained from a study that combines the use of energy forecasting models with an assessment of air pollution impacts on mortality *(30)*, we find that the total economic contribution of the NDC interventions in 2030 ranges between US$ 3.5 billion and US$ 14.3 billion (Table A2.16). This is the avoided cost emerging only for the year 2030, and the value is larger when considering the cumulative value between 2020 and 2030 or beyond. This type of economic valuation should be considered when estimating the cost of climate mitigation, and the resulting benefits (e.g. reduced energy spending and energy cost), to which the health co-benefit should be added. To compare costs and benefits, the estimation of the latter should be performed taking into account the full lifetime of the investment.

As Table A2.16 shows, we calculated the economic co-benefits of avoided morbidity compared to the NDC reference scenario in 2030 (data taken from Table A2.14). Table A2.16 also shows the economic co-benefits of avoided mortality compared to the NDC reference scenario in 2030 (data taken from *(30)*). By comparing the two co-benefits (avoided morbidity and avoided mortality), we also indicated in Table A2.16 the share of morbidity co-benefits compared to economic benefits of avoided mortality.

Table A2.16. Validation of economic co-benefits of avoided morbidity and mortality compared to the NDC reference scenario in 2030

Scenario	Economic co-benefits (morbidity) vs NDC reference in 2030	Economic co-benefits (mortality) vs NDC reference in 2030	Total co-benefit	% of morbidity co-benefits
Business as usual (BAU)	US$ 835 620 000	US$ 2 630 000 000	US$ 3 465 620 000	24.1%
Current ambition	US$ 1 936 640 000	US$ 6 100 000 000	US$ 8 036 640 000	24.1%
High ambition	US$ 3 683 060 000	US$ 10 650 000 000	US$ 14 333 060 000	25.6%

The results of Table A2.16 indicate that under every scenario, the morbidity co-benefits represent 24–26% of the total co-benefits of avoided mortality and morbidity, compared to the NDC reference scenario in 2030. These percentages are slightly higher than the ones indicated by Enriquez et al. *(29)*, and show that a validation of the assumptions and results (performing triangulation between studies providing assumptions and studies providing outcomes) is useful to evaluate the consistency of the analysis.

Finally, we can compare the cost of realizing Pakistan's ambition for emission reduction from the NDC to the cumulative health co-benefits of reducing air emissions (Table 20). The cost of energy-related intervention is estimated to be US$ 101 billion by 2030, growing to US$ 166 billion by 2040. The "current ambition" scenario, which represents NDC ambition, would avoid US$ 10 billion by 2030 and up to US$ 110 billion by 2050. Considering that the lifetime of the investment made in the NDC to reduce emissions ranges between 20 and 40 years (reaching 2060), the health co-benefits alone would more than offset the investment required. If we consider avoided energy costs, job creation and other positive economic benefits resulting from these outcomes, investing in emission reduction is a viable investment, and even more so when considering health co-benefits.

Climate proofing of health facilities

Retrofitting non-structural items

Health care facilities are vulnerable to extreme weather events and should anticipate the climate risks of their location *(31)*. Climate change considerations should be included in institutional-level vulnerability assessments that are part of preparedness planning. Non-structural components are part of the institutional health care infrastructure. Examples of non-structural items include interior components, such as suspended ceilings, as well as architectural components such as windows and roofing *(31)*.

i. **Investment:** The cost of retrofitting non-structural items is generally 1% of the value of a hospital *(32)* (HCWH, 2018). We used the cost estimate per room for the expansion of the Federal Government Polyclinic Hospital (FGPH) in Islamabad (600 beds for Rs 4 billion, or US$ 20 million *(33)*) to estimate a cost of US$ 207 100 for retrofitting non-structural items in the current hospital which has 545 beds.

ii. **Avoided costs:** The average energy intensity of a hospital in India (the closest statistic we could find to Pakistan) is 380 kWh/m^2/year *(34)*. Using this assumption, the calculated annual energy consumption of the FGPH (13 006 m^2 *(35)*) comes to 4 942 280 kWh. Considering that the unit price of electricity from the grid in Pakistan is US$ 0.14 per kWh *(36)*, the annual electricity cost of the FGPH amounts to US$ 691 919. Since energy efficiency retrofit measures in hospitals can save 22.5% of energy demand on average *(31)*, the total avoided cost would amount to US$ 155 682 per year.

Implementation of passive and active design measures

i. Passive design measures include building orientation, air sealing, continuous insulation, windows and daylighting, and natural air circulation. The potential to improve building design features is typically more constrained in existing buildings than in new ones *(37)*. This is because there are limitations to changing the use of sun, wind and vegetation or adjust the orientation and geometry of existing buildings. On the other hand, it is still possible to improve passive design in existing buildings (e.g. via improved thermal insulation, more active utilization of sunlight) *(37)*.

ii. **Investment:** The cost of implementing passive design measures, to achieve a minimum reduction of 20% in energy and water use in existing buildings, amounts to US$ 13.25 per m^2 *(37)*. Since the FGPH covers 13 006 m^2 *(35)*, the total cost amounts to US$ 172 330 (with annual operation and maintenance cost in the range of 5% of the initial investment).

iii. **Avoided costs:** According to the IDB (2020)*(37)*, implementing passive design measures in existing hospitals results in saving 72 kWh/m^2 and 0.86 m^3 of water per square metre. Considering that the unit price of electricity from the grid in Pakistan is US$ 0.14 per kWh *(36)*(Ali, Arif, & Theppaya, 2021), and that a cubic metre of water in Pakistan costs roughly US$ 0.01 *(38)*(Qureshi & Ashraf, 2019), the total estimated annual saving for the FGPH *(35)* amounts to US$ 131 164.

Electricity system hardening (undergrounding)

Storms and other extreme weather events can damage electricity distribution systems, negatively impacting local communities that suffer from the disruption of essential services, including health care *(39)*. A strategy to strengthen the resilience of energy systems (referred to as "system hardening") consists of moving transmission lines underground to avoid climate-related damage.

i. **Investment:** Converting overhead distribution lines to underground ones is estimated to cost on average US$ 3 894 990 per km in urban areas *(39)*. Assuming an average length of 5 km to reach the first transmission node, the total cost amounts to US$ 19 474 948. Annual operations and maintenance costs are assumed to be 10% of the capital cost.

ii. **Avoided costs (economic):** Undergrounding transmission lines allows to avoid power outages from extreme weather events. It has been estimated that a minute of power outage in a hospital costs roughly US$ 7900 per minute *(40)*. Assuming that this intervention would allow to avoid 2 hours per month of power outages (24 hours per year, a conservative estimate), the total avoided cost would amount to US$ 11 376 000 per year.

iii. **Avoided mortality risk:** The literature shows that the risk of mortality increases by 43% on days in which health facilities are affected by a power outage for 2 or more hours *(41)*. Considering that the FGPH has a capacity of 545 beds *(35)*, assuming that 6.2% of patients are at risk at any given point in time *(42)* and that average hospital stay is 1 month per patient, the total avoided patients at risk of mortality comes to approximately 14.5 per month, or 174 each year, when power outages are fully avoided.

Solar panels and battery storage

A second option to secure reliable power supply for hospitals is to invest in a distributed energy system (DER), such as microgrids, combined heat and power systems, and rooftop solar installations coupled with battery storage.

i. **Investment:** The estimated annual energy consumption of the FGPH is 4 942 280 kWh. Considering that the capacity factor of solar PV is 0.16, and that the unit cost per MW of solar PV amounts to US$ 883 000 *(43)*, the cost of solar PV to fully satisfy demand over 24 hours (making use of battery storage) amounts to US$ 6 227 216. When including storage, with a cost per kWh of US$ 625 *(44)*, the total cost of batteries amounts to US$ 4 231 404. Overall, the cost of solar PV and batteries adds up to US$ 10 458 620. If implemented in conjunction with retrofitting measures, allowing to reduce energy demand by 22.5% *(31)*, the total cost of solar power and battery storage would amount to US$ 8 105 431. On the other hand, annual operations and maintenance costs are 2.26% of the capital cost of the system *(43)*.

ii. **Avoided costs (economic):** Solar PV and batteries would provide reliable electricity supply for the hospital, avoid power outages from extreme weather events. It has been estimated that a minute of power outage in a hospital cost roughly US$ 7900 per minute *(40)*. Assuming that this intervention would allow to avoid 2 hours per month of power outages, the total avoided cost would amount to US$ 11 376 000 per year. Besides, solar PV would allow to avoid the costs to import 4 942 280 kWh, which is the estimated annual energy consumption of the FGPH. Considering that the unit price of electricity from the grid in Pakistan is US$ 0.14 per kWh *(31)*, the annual electricity avoided cost amounts to US$ 691 919. If we consider the impact of retrofitting measures, which reduce electricity demand, the avoided electricity costs from solar PV amount to US$ 536 237.

iii. **Avoided mortality risk:** Since solar PV would allow to avoid power outages, the avoided mortality risk is the same as the one of "electricity system hardening (undergrounding)".

The undergrounding of the electricity system is characterized by a higher cost when compared to solar panels and batteries. This is also an intervention that generally concerns the municipality, rather than hospital management. As a result, we consider the two options as alternatives to one another. We also acknowledge that the undergrounding of transmission lines will generate avoided costs for citizens and businesses, a value that is not included in our analysis.

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Department of Environment, Climate Change and Health
World Health Organization (WHO)
Avenue Appia 20 – CH-1211 Geneva 27 – Switzerland
https://www.who.int/teams/environment-climate-change-and-health

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