: vivideconomics



Impacts of higher temperatures on labour productivity and value for money adaptation: lessons from five DFID priority country case studies



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Executive Summary

This report assesses the impact increased temperatures will have on labour productivity in select **DFID** priority countries, and maps out the adaptation options that could mitigate these impacts. The labour productivity impacts of climate change could be substantial, even when ignoring the risk of extreme climate outcomes. Through a stylised model of five case study countries, the analysis finds that even under a central climate change scenario – where temperature increases are not expected to be drastically higher than today – by 2050 up to 20 per cent of effective working hours could be lost due to decreased labour productivity, with a substantial negative impact on economic output.

This research makes four key contributions to the evidence base on rising temperatures and their impacts on labour productivity.

First, the report provides a focussed synthesis of academic and grey literature on the relationship between temperature and labour productivity.

There is a broad consensus in the literature – from a large number of experimental studies across various contexts and occupations – that worker productivity tends to decline once 'heat stress' breaches a threshold level. Heat stress results from various factors, including air temperature, humidity, wind speed, exposure to direct sunlight, and the intensity of work being undertaken. The threshold level will vary depending on context, and there are different approaches to quantifying the relationship between temperature and labour productivity. Nevertheless, as a rule of thumb, the impacts on labour productivity for the most intense work start at around 26°C on the Wet Bulb Globe Temperature index, a common measure of heat stress (explained further in Appendix B).



Source: Vivid Economics model







Second, the report develops a flexible first-of-its-kind modelling framework to estimate the impact of rising temperatures in different countries. This stylised model of a national economy is then calibrated to estimate the impact of various climate change scenarios in five DFID priority countries, covering different contexts: Ethiopia, Ghana, India, Jordan and Tanzania. The literature review provides the basis for the technical assumptions made in the quantitative modelling framework.

The main finding from the model is that labour productivity losses due to high temperatures may be substantial, even under relatively moderate climate scenarios. Effective working hours could be reduced by up to 20 per cent by 2050 (for example in India), and Gross Value Added – a measure of national economic output – may fall by up to 3 per cent (for example in Ghana). These aggregate numbers mask important distributional effects, as the losses are to a large extent concentrated in traditionally low income sectors such as agriculture and construction. There are also important seasonal variations, with India losing almost half its effective working hours during the hottest few months of the year.



Estimating the impact on effective working hours over time (baseline, 2030 and 2050)

Notes:The three columns for each country represent baseline (turn of the century), 2030 and 2050. In the top half of the
figure, light shading indicates remaining effective full-time workers after heat impacts, medium shading indicates
effective reduction in workers due to baseline temperatures, dark shading indicates workers lost under additional heat
increases in 2030 and 2050.In the bottom half of the figure, thick hatching represents proportional losses due to current temperature level, thin

In the bottom half of the figure, thick hatching represents proportional losses due to current temperature level, thin hatching represents further proportional losses due to heat impacts from climate change in 2030 and 2050. Vivid Economics

Future temperature increases account for about half of the predicted GVA losses by 2050 in three of the five countries. Current temperatures are already estimated to result in substantial economic losses in the case study countries. These losses are the result of both a high pre-industrial 'baseline climate' and

Source:





temperature increases experienced so far due to climate change. The economic losses are estimated to double by 2050 under median climate change scenarios in Ethiopia, Jordan and Tanzania; that is, about 50 per cent of the GVA loss expected by the middle of the century is associated with future climate change, and the remaining 50 per cent with current (turn of the century) temperatures. A significant rise is estimated in Ghana and India (where baseline temperatures are already high and more extreme losses are already being felt).

The results are sensitive to modelling assumptions – and should be interpreted as a conservative lower bound. In particular, moving to a more extreme climate change scenario, or using a less conservative relationship between temperature increases and labour productivity, would both roughly double the impacts on GVA. Furthermore, this report only estimates the immediate response of labour productivity to an in-hour increase in temperature; it does not incorporate estimates of exposure to persistently higher temperatures, nor does it include any potential impacts on economic growth rates.

Nonetheless, the modelling work confirms that heat-related labour productivity losses are important in both absolute and relative terms. The estimated GVA impacts are on a par with other expected climate change impacts, such as risk of increased health impacts, tourism flows and revenues, and so on, even for a relatively modest increase in temperature. The loss of effective working hours in key sectors of the economy will also have important distributional and poverty effects.

Third, the report sets out a comprehensive mapping of potential adaptation options. It considers who the primary driver of adaptation would be between individuals, firms and the government, and provides a qualitative ranking of a longlist of adaptation options on their potential to provide large scale, effective adaptation. A shortlist of 17 adaptation measures are then described in more detail and their potential value for money is assessed in a range of contexts.





Note: (1) The size of each bubble indicates the 'potential scale of impact' assessment – larger bubbles indicate larger impact. (2) The colour of each bubble indicates the 'feasibility of implementing the measure' assessment – orange indicates low feasibility, yellow indicates medium feasibility, green indicates high feasibility. (3) Bold typeface indicates measures included in the shortlist for this analysis.

Source: Vivid Economics

Finally, the report describes a decision making framework for adaptation faced with uncertainty and diverse local contexts. Adaptation is complex because the optimal decision for the portfolio of adaptation measures is highly context specific. There are no generally applicable solutions or 'silver bullets'. Decisions also depend on the nature of the future climatic changes, and at the local scale these remain largely unknown.

While the importance of local contexts prevents a general ranking of adaptation measures, there are rules of thumb for when particular solutions provide most value for money. In general, behavioural measures such as changing working hours to avoid the hottest parts of the day/year, and passive adaptation options such as regular drinks breaks, are likely to be more effective than technical solutions, especially where the impacts are most keenly felt by high-intensity outdoor workers. Adjustments to building design are most suitable for a shift in base temperature, while air conditioning and behavioural measures can respond more flexibly to short temperature peaks. The merit of energy intensive solutions like air conditioning depends on the carbon content, cost and access to energy.





Adaptation measures must be able to accommodate different potential climate scenarios. The

framework sets out the importance of uncertainty around the evolution of climate change, and sets out the value of measures that increase flexibility in response and/or which would be 'low-regrets' – that is, they are likely to be beneficial to implement in any future state of the world. It also sets out the contextual factors that will determine the value for money of adaptation options in a specific setting, such as the extent the population is rural or urban, the type of work carried out in the economy (today and in the future) and implications for energy consumption.





1

1 Introduction

Vivid Economics has been commissioned by the Department for International Development (DFID) to carry out a study seeking to contribute to two broad objectives:

- Develop a deeper understanding of how higher temperatures will affect labour productivity in DFID priority countries, including the magnitude and significance of these impacts compared to other factors affecting labour productivity and other economic impacts of climate change;
- (ii) Identify cost-effective measures DFID priority countries could take to address these impacts, and assess the value for money of such measures.

PART A of this report responds to the first of these objectives, setting out the potential scale of the problem in absolute terms, and also relative to other impacts of climate change, and of other factors affecting labour productivity.

PART B then examines ways in which countries could adapt to higher temperatures to mitigate potential labour productivity losses. While understanding the relative importance of heat impacts on labour productivity is important, the potential impacts should not be considered in isolation from consideration of cost-effectiveness of adaptation options. Section 10 and Section 11 then conclude with policy recommendations, concluding remarks and areas for further research.

This applied study follows five illustrative country case studies: Ethiopia, Ghana, Jordan, India and Tanzania. These were selected to provide a varied set of national economies which can provide stylised examples for other DFID priority countries. In particular, the case study country contexts vary by base temperature levels and distribution of temperature across the year, expected changes in temperature levels in the coming decades, and in economic structure.¹

Temperatures have risen substantially over the course of the last century – in particular the last 50 years – and climate models predict further increases over the coming decades. Heat stress already has important effects on labour productivity today, and this will increase as temperatures rise. Understanding the main drivers of impacts on labour productivity and economic outcomes will help target policy recommendations and adaptation options.

The focus is on the contemporaneous labour productivity losses associated with temperature increases in a given hour. Specifically, this report considers the immediate (in-hour) impact of high temperatures on labour productivity. This is a conservative estimate of the total impact of high temperatures, as it does not





¹The analytical tools have been developed so as to be flexible to be applied to other countries with minimum pre-processing of input data required. A full description of the process followed to select these countries is provided in Appendix A.

include any cumulative / longer-term impacts on productivity of exposure to persistently high temperatures, nor of the impact of high temperatures on economic growth through reduced labour productivity.

Productivity <u>increases</u> that might be associated with higher temperatures at the lower end of the scale are not included in this analysis. Temperature increases from a lower base (that is $15^{\circ}C - 20^{\circ}C$) may increase productivity (Figure 1). The purpose of this study is to quantify and propose adaptation options to labour productivity impacts at higher temperatures, rather than to consider ways to increase indoor temperatures to optimal levels for workers currently working in a sub-optimally cold environment.



Note:General and approximate relationship shown as illustrative example only.Source:Vivid Economics, based on Seppänen, Fisk, & Lei (2006)

The focus on contemporaneous impacts of heat increases on labour productivity means the estimates presented in this study should be interpreted as conservative lower-bounds. Some potentially important cumulative long-term mechanisms are not included:

- <u>Lagged short-term impacts of temperature increases.</u> We do not consider the cumulative effect of temperature increases over several days. For example, a consistent 30°C may be more problematic than a high of 35°C, but with cooler nights that allow workers to recover.
- <u>Higher temperatures may affect human capital accumulation</u> over the very long-term through health and education effects. While there is some emerging evidence on the impacts of temperatures on factors affecting human capital accumulation, these are not included within the scope of this study.
- <u>Biological acclimatisation to persistently higher temperatures.</u> It is possible that over a longer time
 period, workers may to some extent adapt to the higher temperatures, in which case the short-run effects
 may be to some extent reduced over time. There is limited evidence to support any firm assumption here.



PART A

Estimating the potential impact of higher temperatures on labour productivity







2 The Evidence Base

This section presents a review of literature relating to the impacts of increased temperature on labour supply and labour productivity.

2.1 Literature review process and objectives

The review identifies a limited set of core materials focused on the specific area of labour productivity impacts of temperature increases. While there is a wide range of climate change literature available, this review targets the most relevant to the issues of reduced labour productivity, by:

- 1. <u>Beginning with a list of core contributions to the field</u>, drawing on the input and recommendations from experts in the project team and at DFID;
- 2. Expanding the literature review based on citations and key references from the initial list;
- 3. <u>Validating literature through expert review</u>, provided by Professor Sam Fankhauser and Dr Hélia Costa, to ensure core literature and key insights are included;
- 4. <u>Applying an algorithmic search tool</u>, 'Publish or Perish',² to identify additional literature not identified through the previous steps as a robustness check.

The evidence includes peer-reviewed academic analyses and journal articles, working papers and a smaller volume of grey literature and commissioned research.³ It is a focussed review and is not intended to represent an all-encompassing picture of literature on the full range of possible heat impacts on human health, nor of climate change impacts more generally. The review provides context for this study and ensures robustness of the technical approach.

The literature review is also focussed on areas where there is a relatively strong evidence base. In particular, we build on a large number of established empirical papers estimating the relationship between temperature increases in different environmental settings, and labour productivity.

In other areas, where the evidence base is less well developed, we provide a shorter review of key contributions, especially where not directly relevant for the modelling approach. A key example of this is the long-term effect of higher temperatures on the *growth* rate of labour productivity (as opposed to the short-term level effect studied in this report).



²Publish or Perish (Harzing, 2007) is a software tool that retrieves and analyses academic citations from the Google Scholar and Microsoft Academic Search databases, and presents information on citations and related statistics. For this analysis, we conducted keyword searches of the Google Scholar databases, identifying three additional references to be included in the literature review (Kjellstrom & Crowe, 2011; Roson & Sartori, 2016; Sahu et al., 2013).

³ See References on p. 122

2.2 Temperature increases and economic damages

Economic studies and statistical analyses identify a clear relationship between increasing temperatures and economic damages:

- Dell, Jones, & Olken (2012) find that a 1°C increase in temperature in a given year is associated with a 1.4 per cent within-year decrease in per capita income in poor countries.⁴ The authors also find evidence that temperature changes in one year affect future income levels, suggesting that temperature increases affect both *income levels* and the *income growth rates*, and that this may be driven through impacts on agricultural and industrial output.
- Horowitz (2009)predicts that a 1°C temperature increases across all countries would lead to a 3.5 per cent reduction in Gross Domestic Product (GDP).
- Burke, Hsiang, & Miguel (2015) estimate substantially larger damages; that rising temperatures due to climate change could lead to a global reduction in GDP per capita of 23 per cent by 2100. This average masks variation across regions, with some (northern) countries likely to see increases in GDP per capita, while others projected to see larger decreases with losses of up to 75 per cent of GDP per capita in South Asia, Southeast Asia, the Middle East and North Africa (MENA) and Sub-Saharan Africa.

In general, studies estimating the overall relationship between temperature and economic damages do not identify the individual impact channels. These channels include reduced labour productivity, reduced agricultural productivity and damage to public health. Analyses of the 'global' relationship between economic output and temperature changes tend to stop short of providing a detailed decomposition of the overall relationship into these individual mechanisms, although some provide comparative evidence on the scale of economic and social impacts from other aspects of climate change (more detail in Section 5.1).

For the agricultural sector, there may be a dual effect of temperature on economic output, as once temperature increases beyond a threshold there will be both human labour and direct physical impacts on crops. Studies identify that both the supply of labour and the 'performance' of labour decrease once temperatures pass a threshold between 20°C and 30°C, and that agricultural output such as maize yields also start to decrease around a similar threshold point (Burke, Hsiang, & Miguel, 2015).

Higher temperatures have been linked to increased human mortality, especially among vulnerable populations. Identifying the relationship between ambient temperature and mortality is not trivial, as mortality rates depend on a number of other factors, such as air pollutants, demography, income-levels, and so on. In general, mortality risk increases at high temperatures particularly for vulnerable populations, such as the elderly, very young, or those suffering from respiratory or cardiovascular illnesses (Basu, 2009).





⁴ The authors define 'poor' countries as 'below-median PPP-adjusted per capita GDP in the first year the country enters the dataset'.

The impact of increased temperatures on human health has been subject to relatively few studies, although there is evidence of increased healthcare costs from heat-related illnesses. For example, a recent study, noting the lack of evidence to date, estimates the economic costs to the US healthcare system associated with heat-related illnesses (Schmeltz, Petkova, & Gamble, 2016). The study also found a wide distribution of impacts, with racial/ethnic minorities, low income families, and men disproportionately affected. Similarly, another U.S. study found admittances to accident and emergency rose quickly as temperatures increased – for example admissions for heat illnesses increased by 393 per cent for a 10°F (around 5.6°C) increase in temperature (Basu, Pearson, Malig, Broadwin, & Green, 2012).

2.3 Temperature increases and labour productivity

Rising temperatures lead to 'thermal stress' on people, with impacts on both health and human capital through increased morbidity and mortality and decreased cognitive functioning. These will have direct welfare impacts through increasing levels of discomfort, and through affecting the labour force's ability to work effectively, and may in turn lead to social or political stresses through increased levels of criminality and violence or political instability (Heal & Park, 2013).

Rising temperatures may also have long-term impacts on labour productivity growth. Factors affecting the effectiveness of labour are likely to have much larger long term impacts on economic growth than a simple 'one-off shock'.

Growth effects may be substantial, although the evidence is mixed. Comparing models that incorporate impacts on growth rates with traditional models that do not consider these effects suggests that impacts on growth rates may be substantial in the long run. Dietz & Stern (2015)estimate that by 2200 consumption per capita could be 11 per cent to 24 per cent lower when climate change impacts drivers of growth than under standard modelling, depending on how climate change affects the drivers of growth. However, the debate on whether temperature affects output as a one-off shock or persistently affects growth rates has not yet been settled either in theoretical or empirical terms Heal & Park (2016).

Models of temperature impacts on labour productivity typically identify short-term responses to temperature shocks. In these models, task performance potentially rebounds when temperatures decrease to previous levels. However, increased temperatures could also reduce the rate at which productive capital accumulates – through for example rates of education which affect development of human capital – or result in permanent damages to the existing capital stock Heal & Park (2016).

Various studies estimate the empirical relationships between temperature increases and growth rates. Some identify impacts of temperature increases on both income levels and growth rates in poor countries (Dell, Jones, & Olken, 2012) or note that temperature increase may affect manufacturing output consistently into the future (Cachon, Gallino, & Olivares, 2012). However, others find that while temperatures have an effect on output that persists beyond the initial shock, this effect declines over time (Heal & Park, 2013).

The literature on the effects of temperature increases on labour productivity brings together analyses of biophysical responses to temperature with economic studies or modelling of climate change impacts.





The evidence base exploring the relationships between climate change-induced temperature changes and labour productivity broadly fits into three categories:

- 1. <u>human biophysical responses to temperature</u>, under current conditions or under future climate change;
- 2. <u>national-sectoral analyses</u> of the impacts of temperature increases on economic production in different sectors of the economy; and
- 3. <u>economic modelling</u> that applies findings from the biophysical response literature and nationalsectoral analyses to identify the wider impacts of temperature increases on labour productivity, both in broad settings such as regional or global studies, or in specific contexts such as cities.

2.3.1 Human biophysical responses to temperature

Figure 2 sets out the channels through which bio-physical responses to increased temperature affect human wellbeing and economic outcomes. This figure, adapted from Kjellstrom et al. (2016), highlights in orange the mechanism which is the focus of this study – namely reduced work capacity and productivity.

There are various other ways in which heat can affect economic outcomes and human wellbeing. These are not covered in detail here and fall outside the scope of this study, but include:⁵

- heat stroke resulting in heat exhaustion or death;
- exacerbation of diseases and damage of vital organs including heart overload and kidney damages;
- injuries from accidents and occupational injuries as a result of diminished human performance capacities;
- behavioural or mental health impacts due to heat exhaustion risk of accidents;
- reduced ability to conduct physical activity outside of the workplace, resulting in less effective use of time outside of work; for example on caring for dependents, household chores and so on and a reduction in 'active' forms of transportation which may raise obesity levels / lower general health.

There is a substantial body of research exploring broader biophysical responses to heat among workers, beyond diminished performance capacity. This literature includes experimental studies and epidemiological analysis of the impacts of heat stress and strain on human health outcomes.⁶



⁵ A full discussion of these other impact channels can be found in Kjellstrom et al. (2016).

⁶ For example, see the overview of evidence in Kjellstrom et al (2016), based on studies including a multi-country observational analysis (Gasparrini et al., 2015), a meta-analysis of epidemiological studies (R. S. Kovats & Hajat, 2008) and national analysis of heat impacts on specific diseases, such as renal diseases in Australia (Hansen et al., 2008).



Figure 2. Heat stress can lead to a number of health issues among workers, including affecting labour productivity

 Note:
 Orange boxes represent impact mechanisms considered in this analysis. Blue boxes represent other health and economic issues relating to heat stress beyond the scope of this analysis.

 Source:
 Vivid Economics, based on Kjellstrom et al. (2016)

2.3.2 National-sectoral analyses

Heal & Park (2016) provide a typology which sets out three mechanisms through which heat affects the total productivity of the labour force:

- (i) *labour supply*, total hours that individuals choose to work or whether they enter the labour force,
- (ii) *labour effort*, the amount of effort workers choose to expend while at work, and
- (iii) *labour productivity*, the degree to which workers' effectiveness is degraded while at work.

On the first two of these mechanisms, labour supply and effort, there is relatively limited evidence. There is some indication that workers in high temperature environments reallocate hours from work hours



and outdoor leisure to indoor leisure (Graff Zivin & Neidell, 2014).⁷ However, the authors note that there is limited evidence on workers reducing effort in response to heat.

There is a much richer literature on the third mechanism, the impacts of heat on labour productivity. Hallegatte et al. (2016), Kjellstrom et al. (2016) and Heal & Park (2016) provide meta-studies of the evidence on the link between heat and labour productivity. The majority of the studies summarised in these reviews examine this relationship in a specific national-sectoral context, for example exploring looking at one particular industry or context in a specific country, or synthesising existing studies within these contexts.

All studies find substantial reductions in labour productivity for temperature increases above a certain threshold. While the degree of impact varies across studies, they indicate that once a threshold value is breached, increasing temperatures are associated with decreasing labour productivity, and that such decreases increase with the temperature level.

Caution should be applied when comparing the literature, which often is based on different underlying assumptions and/or may be context specific. In some cases, the technical approach is not comparable. For example, different studies use different measures of heat stress. Most, but not all, are based on the 'Wet Bulb Globe Temperature' (WBGT) index of heat stress,⁸ which incorporates air temperature, solar radiation, and humidity (Kjellström, Flouris, & Nybo, 2016).In other cases, the studies are only directly applicable to specific sectoral or regional contexts, and care should be applied in transferring these values out of the context of the original study.⁹

The outputs from these and other studies have been combined to estimate a continuous relationship between temperature (measured as WBGT) and labour productivity. These measures typically identify the productivity level either as a percentage value of full productivity, or as percentage productivity loss relative to full productivity. Approaches to estimating such relationships commonly vary in two key ways:

- 1. <u>Disaggregation of the relationship by intensity of work.</u> Work intensity may vary substantially across professions, for example office activities tend to be less intense than construction or manufacturing activities. In technical models, work intensity is typically measured using the 'average metabolic rate' associated with the activity in Watts (W), indicating the amount of energy used by the body in carrying out activities.
- 2. <u>Identifying the underlying relationship or providing 'safeguarding' limits to work.</u> Most studies and all experimental evidence identify the relationship between heat and labour productivity. However,





⁷ Reviewed in Heal & Park(2016) in a previous format, as a 2010 National Bureau of Economic Research working paper.

⁸ For a fuller description of the WBGT see Appendix B.

⁹ See Appendix C – Temperature Impacts on Productivity for summaries of all these studies assessing impacts of temperatures on labour productivity.

some draw on measures developed by public bodies tasked with safeguarding worker health. These measures provide guidelines for how workers should reduce activity to ensure they do not suffer ill effects from raised temperatures. The measures are meant to safeguard all workers from such effects, rather than representing how the average worker responds to temperature increases. This 'standards' based estimate of the relationship typically suggest greater reductions of work activity than experimental evidence and studies (Kjellstrom, Lemke, Otto, Hyatt, & Dear, 2014).

Figure 3 shows various estimates of the relationship between temperature and productivity, some of which are based on studies summarised in Appendix C, some are based on international standards as discussed above, and some have been independently determined through additional analysis to develop the independent point estimates into a reaction function. Figure 3 shows four sets of response functions, each of which include a number of functions for different levels of work intensity (measured in Watts):

- 'Hothaps' relationships from the High Occupational Temperature Health and Productivity Suppression study, based on experimental data;
- Sahu-Wyndham relationships, based on combined experimental data from the Sahu, Sett, & Kjellstrom (2013) and Wyndham (1969) studies in Appendix C;
- relationships as set out in the ISO standards, also assuming a maximum loss of 90 per cent of productivity;
- relationships from Kjellstrom, Kovats, Lloyd, Holt, & Tol (2009), based on ISO and US standards.

The degree of productivity loss varies based on the level of work intensity, underlying data and type of study. While some studies model gradual productivity losses occurring from temperatures as low as 10°C to 15°C, the most recent experimental studies (Hothaps, represented by the orange shaded lines) show a steeper productivity loss function but that only comes into effect once temperatures increase above 25°C. A more disaggregated set of graphs showing the sources of the various modelling relationships between heat and labour productivity is provided in Appendix D–Heat : Productivity Relationships.

Prolonged exposure to high temperature may lead to further reductions in productivity. For example, Sahu et al. (2013) find that productivity levels are generally tend to be lower later in the working day at high temperature levels. Furthermore, temperatures that remain persistently high – for example overnight – reduce biological recovery time and may therefore have further compounded impacts on productivity.







Figure 3.

Note: Solid lines represent the central estimates of the relationship for moderate intensity work (300W) from different sources. Small dashed lines represent estimates from the same source for low intensity work (200W), long dashed lines represent estimates from the same sources for high intensity work (400W or 500W).

Vivid Economics, based on Kjellstrom et al. (2015), Kjellstrom et al. (2014), Kjellstrom, Kovats, Lloyd, Holt, & Tol Source: (2009)

2.3.3 **Economic modelling**

A number of studies have applied the evidence base on the relationship between temperature and labour productivity to model the impacts of temperature increases on larger scales. Building on the evidence base on labour productivity responses to heat stress in experiments or in specific real world contexts, studies have sought to estimate the broader implications of heat stress for labour output. These include national, regional and global modelling, and applications to specific contexts, such as cities. An overview of key modelling evidence is presented in Table 2.

While different modelling exercises identify different outcomes depending on the scale, assumptions and time frame, all suggest that heat stress is already a significant economic cost to society. The models suggest that this is likely to increase over this century, and that the costs are likely to be particularly severe in poorer or developing regions. The key results from these studies provide context and comparators for the results of the technical model (Section 4).

No existing modelling incorporates impacts of temperature increases on growth rates or the drivers of economic growth. The models commonly apply evidence on reductions to effective labour supply as a shock in given years, but as yet no modelling approaches incorporate the potential longer-term impacts of temperature increases on the factors underlying economic growth, such as human capital.





Study	Context	Findings
Kjellstrom et al. (2014)	Models impact of heat on labour productivity by region in 1975, 2030 and 2050 for sectors with different work intensity: agriculture (high), industry (moderate), services (light)	Climate change will reduce available working hours in all regions, with a capacity loss of up to 5% loss by 2050 in affected areas. The largest impacts are in Sub-Saharan Africa, South Asia, South East Asia and Oceania
Kopp et al. (2014)	Models the reduction in the proportion of time working during the hottest months in the United States of America to 2099	Under a high climate change scenario, heat increases would lead to significant productivity losses of up to 3% across almost all of the USA
Costa, Floater, Hooyberghs, Verbeke, & De Ridder (2016)	Models the impact of heat stress on labour productivity in Antwerp, Bilbao, and London to 2100, including sectoral analysis of expected costs	In a warm future year (2081-2100), total losses to the urban economy range between 0.4% of GVA for London and 9.5% for Bilbao. Some sectors are more exposed to economic losses – for example, financial services, public administration and retail trade are most exposed in London
Kovats, Lloyd, Hunt, & Watkiss (2011)	Assesses the potential impacts and economic costs of selected health impacts in Europe due to climate change in 2080, including labour productivity effects	Under one scenario, Southern Europe is estimated to see average productivity losses between 0.4% and 0.9% by 2080. Total productivity losses for Europe could cost between EUR 300 million and EUR 700 million per year by 2080, (less under a scenario with increased mitigation efforts)
Roson & Sartori (2016)	Estimates the damages linked to reduced labour productivity for 140 'regions' in the Global Trade Analysis Project database, for a 3°C temperature increase	A 3°C temperature increase is projected to lead to costs of up to 8% of GDP in some countries due to impacts on labour productivity, with West Africa projected to be the worst affected
Dunne, Stouffer, & John (2013)	Assesses loss of labour productivity during the hottest months in each part of the world over the period 1975–2200	Reductions in work capacity, during the hottest months already occur at the global level, on the order of 6% to 10%. By 2100, the reductions in the hottest month may reach 20% to 37% , depending on the climate change scenario, though reductions may lower during cool months (1% to 5%). By 2200, reductions in hottest month could reach 61%
Kjellstrom, Lemke, & Otto (2013)	Estimates losses due to heat stress for the hottest month of the year in South East Asia for different work intensities, comparing 1975 with 2050	High intensity work in the sun is most affected, with a 29% loss of annual work hours. Medium intensity work in the sun is projected to face losses of c. 15%, while work in the shade or indoors is expected to see lower losses
DARA & Climate Vulnerable Forum (2012)	Applies estimates of labour productivity loss with temperature to model costs of heat stress in 2010 and 2030, by country	The annual global cost of reduced labour productivity due to heat is projected to increase from USD 300 billion in 2010 to USD 2.5 trillion in 2030. Costs are expected to be particularly high in Sub-Saharan Africa, Central America, South Asia and South East Asia
Zander, Botzen, Oppermann, Kjellstrom, & Garnett (2015)	Self-reported estimates of absent- eeism and reduced performance caused by heat in Australia during 2013/2014 to estimate economic costs of labour productivity	The annual costs of heat stress on workers are c. USD 650 per person across a representative sample of 1,726 employed Australians, suggesting an annual economic cost for the whole workforce of around USD 6 billion , equivalent to 0.33% to 0.47% of Australia's GDP
Kjellstrom et al., (2016)	Models global losses (by region) due to climate change-induced temperature increases comparing 1995 with 2085	The most affected regions are projected to see reductions in total working person-hours of between 1% and 10%. South America, Africa, South Asia, South East Asia and Oceania are projected to be the worst affected regions

Table 1. Various studies estimate the impact of heat on labour productivity (national, regional or global) and economic output

Source: Vivid Economics, based on original research and Kjellstrom et al. (2016)





3 Modelling Approach

In this section we provide a summary of the modelling approach taken to estimate the potential impact of temperature increases on labour productivity. A more detailed description of the model, including assumptions made, is included in Appendix G.

The modelling approach builds on established studies. In particular Kjellstrom et al.'s assessment of the impacts of climate change on labour productivity (Kjellstrom et al., 2014) and Costa et al.'s approach to assess the impact of temperature increases on labour productivity in cities (Costa, Floater, Hooyberghs, Verbeke, & De Ridder, 2016a).

Three steps are worked through to estimate the impact of high temperature on labour productivity:

- 1. <u>hour-by-hour temperature profiles</u> for representative days for each of the twelve months in three time periods: turn of the century, 2030 and 2050;
- 2. <u>a model of 'effective' labour supply</u> for different sectors of the economy for each time period, which feeds into the main model of the economy;
- 3. <u>a *simple multi-sectoral national economic model*</u> that incorporates the impacts of heat on labour supply to project losses in gross value added (GVA) due to current and future temperatures.¹⁰

Wet bulb globe temperature (WBGT) ranges are used to fit a daily temperature profile for 12 representative days (one per month) for turn of the century (baseline), 2030 and 2050. Temperature profiles for each year and country are taken from the World Bank's Climate Change Knowledge Portal (World Bank, n.d.), with a daily temperature profile fit using the average maximum, mean, and minimum temperatures are for each month. The 'baseline' values are based on temperatures over the period from 1986 to 2005, temperatures for '2030' are based on projections for the period from 2020 to 2039, and temperatures for '2050' are based on projections for the period to 2059.

The only modelled response to increased temperature is a reduction in the effective labour supply. All other factors are assumed to be independent of temperature. In particular, growth in the economy is driven by trends in future employment (from ILO projections) and from accumulation of the capital stock only.¹¹ The relative shares of each sector of the economy do not change over time, with employment and capital growth occurring at the same rate in all sectors of the economy.



¹⁰ Gross value added (GVA) and gross domestic product (GDP) are both measures of national economic output and are broadly comparable. GDP is measured as GVA (production output at current prices), plus taxes on production, minus subsidies to production.

¹¹ For growth in the capital stock, we take the historic average over the past ten years from each country as the starting point, and converge this linearly over time to the average worldwide capital stock accumulation over the last ten years.

The labour response to increased temperatures follows the 'Hothaps' models of percentage loss for each work intensity. These response functions represent the most recent functions based on broad evidence from supporting studies including experimental data, and in particular, follow Kjellstrom, Lemke, Otto, Hyatt, & Dear (2014). Some of the response curves active at lower temperatures result from 'standards'-based response functions (as produced by ISO), which may overstate the direct 'economic' impact of high temperatures which is better estimated by experimental studies.

The response functions reach a maximum productivity loss of between 86 per cent and 90 per cent at 38 degrees Celsius WBGT. This allows for some possibility for limited work (falling to a minimum of 6 minutes per hot hour) even at high temperatures, following Kjellstrom, Lemke, Otto, Hyatt, & Dear (2014) and a similar approach taken in ISO standards. This would underestimate productivity loss if, in fact, all work ceases above certain temperatures – although for the purposes of this analysis temperatures in the case study countries do not reach above 38 degrees WBGT by 2050.





The national economy is simplified to a model where national output is comprised of seven sectors. These are: 'agriculture'; 'manufacturing'; 'construction'; 'other industry'; 'wholesale and retail trade'; 'transport, storage and communication'; and 'other services'.¹²

The *'agriculture'* and *'construction'* sectors are the most exposed, as these are assumed to be carried **out outdoors in direct sunlight.** Working in direct sunlight is assumed to raise body temperatures by a





¹² This approach broadly follows the approach taken by Costa, Floater, Hooyberghs, Verbeke, & De Ridder (2016).

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further 3 degrees.¹³ Outdoor workers also tend to be high-intensity physical work sectors. Other sectors are assumed to be carried out entirely indoors, with manufacturing and industry representing 'medium' intensity, and all other sectors 'low' physical intensity.

For each country, working hours for all sectors are assumed to be the same, and by default are assumed to be from 8 am to 1 pm, and from 2 pm to 5 pm. These assumptions can easily be modified – and are explored further in Section 9.2.





 $^{^{13}}$ This assumption follows (Kjellstrom et al., 2014) and is discussed in more detail in Appendix G – Model Specification.

4 Results

4.1 Projected temperature increases

Temperatures are expected to increase by c. 1.5°C between the turn of the century and 2050 for all five case study countries. Figure 5 shows the expected average annual temperature for each country in the baseline, in 2030 and in 2050, with the increase by 2050 ranging from 1.3°C in Ghana to 1.8°C in Jordan. These average increases are based on the means of the four future scenarios for emissions pathways.¹⁴ Under the scenario with the highest emissions, these increases would be between 0.4°C and 0.7°C greater on average across the year. Sensitivity to the climate change scenario assumptions are presented at the end of this section.

Jordan has the highest variation in temperature across the 12 representative days for each month of the year, with the hottest month seeing mean temperatures of 11°C above the annual average. In general, the increases in average temperatures are very similar to the projected increases in maximum and minimum temperatures, though some countries see different patterns of increases across the year. For example, all temperatures in India (mean, maximum and minimum) will increase more in the December-May than in the June-November periods, increasing by up to 0.6°C more in the most extreme case.



Source: Vivid Economics

By the turn of the century, workers in Ghana and India were already often exposed to temperatures above the 26 WBGT threshold above which labour productivity declines. As shown in Table 2, of the 12 representative monthly days, 10 reach above the 26 WBGT in Ghana, and 8 in India. Of the 96 representative working hours,¹⁵ India already spends 68 hours above 26 degrees WBGT. For outdoor workers in direct



¹⁴ The four Representative Control Pathways (RCPs) used in IPCC's Fifth Assessment Report (AR5).

¹⁵i.e. 8 hours in each of the 12 representative monthly days.

sunlight – which is assumed to add a further 3 degrees (as set out in Section 3) – all the case study countries would already have been experiencing some productivity losses at the turn of the century.

Ethiopia and Tanzania face almost no ambient temperatures in the range of the labour productivity response functions – that is above 26 WBGT. In fact, at the turn of the century, none of the 12 monthly days face ambient temperatures of above 26 WBGT at any point in the working day. The only productivity losses are therefore concentrated in outdoor workers in direct sunlight, where effective temperatures are a further three degrees higher, as shown in the second set of columns per country in Table 2.

While some countries are already heavily exposed to temperatures above 26 WBGT, all countries see an increase in exposure to temperatures which will induce productivity losses. For example, in India the number of representative monthly days exposed to a WBGT of over 26 does not increase, and the total number of hours only increases slightly, as Indian workers were already exposed to a large number of hours above 26 WBGT at the turn of the century. However, the extent of exposure increases substantially, as for those hours that do reach above 26 WBGT they are now on average 4 degrees higher than the 26 WBGT threshold compared to an average of 3 degrees above WBGT at the turn of the century (as shown in Table 3).

By 2050 each of the case study countries faces ambient temperatures above the 26 WBGT threshold, and substantial exposure for outdoor workers. Table 3 shows the increase in exposure to high temperatures for both indoor and outdoor workers, with the blue text showing the increase relative to the baseline temperatures presented in Table 2. For example, Jordan sees a small increase in the number of hours exposed to WBGT above 26 by 2050, and a more important increase in the number of degrees above 26 in those hours where workers are exposed, especially for indoor workers.

	Ethiopia		Ghana		India		Jordan		Tanzania	
2015 temperatures	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Representative monthly days where temperatures between 8am – 5pm reach above 26° WBGT (out of 12)	0	10	9	12	8	9	4	5	0	8
Working hours between 8am – 5pm where temperatures reach above 26° WBGT (out of 96)	0	40	48	84	68	76	20	28	0	32
For hours above 26° WBGT: average degrees in excess of 26 degrees	0	1.3	1.3	2.8	2.7	4.2	1.3	3.0	0	1.2

Table 2. Worker hours exposed to high temperatures under baseline temperatures

Source: Vivid Economics





Table 3.	Worker hours exposed to high temperatures in 2050	

	Ethiopia		Ghana		India		Jordan		Tanzania	
2050 temperatures	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Days where temperatures between 8am – 5pm reach above 26° WBGT (out of 12)	3 + 3	12 + 2	12 + 3	12 -	8 -	10 + 2	4 -	6 + 1	2 + 2	10 + 2
Working hours between 8am – 5pm where temperatures reach above 26° WBGT (out of 96)	12 + 12	56 + 16	76 + 28	92 + 8	84 + 16	100 + 24	24 + 4	40 + 12	8 + 8	40 + 8
For hours above 26° WBGT: average degrees in excess of 26 degrees	1.0 + 1.0	1.9 + 0.6	1.9 + 0.5	3.7 + 0.9	3.4 + 0.7	4.3 + 0.1	2.7 + 1.4	3.5 + 0.5	0.2 + 0.2	2.2 + 0.9

Note:Blue numbers indicate the change from the baseline to the 2050 average change scenario applied in this analysis.Source:Vivid Economics

4.2 Labour productivity impacts of temperature increases

Temperature increases will lead to further reductions in the productivity of labour, on top of already substantial productivity losses under current temperatures. Figure 6 presents productivity losses in terms of the 'equivalent effective workers' lost from the labour force due to heat stress. All countries already experience substantial losses in the proportion of equivalent effective workers due to temperatures at the beginning of the 20th century, with this projected to increase as temperature rise.

As would be expected from Table 2 and Table 3 presenting the raw temperature profiles by country, the largest reductions in effective working hours are in India and Ghana. The top panel of Figure 6 presents the absolute loss of effective workers, where the two firmly shaded bars represent the equivalent number of workers lost due to reduced productivity. The bottom panel shows the relative share of the national workforce lost, expressed as a proportion of the total available workforce if there were no heat-related productivity losses.

The impact on working hours is largely a function of exposure to hours where the temperature reaches above 26 WBGT, and the sectors in which workers are employed (discussed further below). Figure 6 indicates where turn of the century temperatures already result in substantial lost labour hours, and where future temperature increases exacerbate this impact. In relative terms the impact of future temperature increases are particularly pronounced in Ethiopia, Jordan and Tanzania where the baseline temperature is lower. In absolute terms, India and Ghana are the most affected by future temperatures, albeit from a higher baseline impact level:

in India, of an expected workforce of over 600 million by 2050, labour productivity losses will reduce the
effective work hours to an equivalent of below 500 million. This represents the equivalent of around 20





per cent of total workforce hours lost due to heat stress. Current temperatures contribute 15 per cent of this impact, with further temperature rises contributing a further 5 per cent;

- Ghana loses the equivalent of around 12 per cent of workforce hours by 2050, with current temperatures accounting for 8 per cent, and future temperature rises the remaining 4 per cent;
- Jordan experiences limited loss of productive hours in 2015, and while the proportion of hours lost will
 more than double between 2015 and 2050 (the largest proportional increase of any of the case study
 countries) it will remain at a low level. This is primarily driven by a low proportion of workers in the
 agriculture sector and limited exposure of services sectors to heat stress.
- Ethiopia and Tanzania will see reductions in labour productivity of around 4 per cent to 6 per cent in 2050, with future climate change between the baseline period and 2050 more than doubling the loss in effective labour supply.





Source: Vivid Economics

These losses of around 1 per cent to 5 per cent of productivity for a 1.5 °C temperature increase align with the existing evidence on high temperatures and lost labour productivity. The modelled losses in this study fall within the broad ranges in other literature, such as the 3 per cent to 4 per cent productivity loss per 1°C variation estimated by Heal & Park (2016) and the Kjellstrom et al. (2014) projection of a 5 per cent loss in working hours by 2050. The results also align with similar levels of impact observed in sector-





<sup>Notes: The three columns for each country represent baseline (turn of the century), 2030 and 2050. In the top half of the figure, light shading indicates remaining effective full-time workers after heat impacts, medium shading indicates effective reduction in workers due to baseline temperatures, dark shading indicates workers lost under additional heat increases in 2030 and 2050.
In the bottom half of the figure, thick hatching represents proportional losses due to current temperature level, thin hatching represents further proportional losses due to heat impacts from climate change in 2030 and 2050.</sup>

specific assessments, such as Hsiang's (2010) observed decrease in non-agricultural production of 2.4 per cent for each 1°C increase, or Sudarshan, Somanathan, Somanathan, & Tewari's (2015) observation of a 2.8 per cent decrease in manufacturing productivity per 1°C temperature increase.

The productivity losses in response to high temperatures are driven by the exposure of the labour supply in key sectors – in particular agriculture and construction which are outdoor and high intensity. Figure 7 shows the loss of effective labour supply in Ethiopia, Ghana, India and Tanzania will be heavily driven by impacts in the agriculture sector. In particular, the dark blue bar shows that agriculture accounts for over 60 per cent of lost work hours in all countries except Jordan. Here, where the structure of the economy is very different, workers in construction – shown by the yellow bar in Figure 7 – are by far the most affected, and account for just over 50 per cent of lost work hours due to reduced productivity.

Not only is agriculture the relatively most exposed sector – as it is high intensity and in direct sunlight – it also accounts for large shares of total employment in most of the case study countries. Across the five case study countries, the share of employment in agriculture is between 45 per cent and 73 per cent for all countries except Jordan, where it is just 2 per cent.¹⁶ In contrast, while individual workers in the construction sector are similarly exposed to productivity losses due to temperature increases, the aggregate impact of these effects is more limited due to the much smaller number of workers in the sector – though construction remains the second largest share of lost productive labour, and the largest contributor to lost effective labour in Jordan.

These productivity decreases may have implications for equality and poverty reduction, as they are felt most keenly by workers in sectors that are typically low income. In particular, outdoor workers in agriculture and construction may be relatively lower earners more likely to be around the poverty line. If lower productivity translates into lower salaries in what are often already relatively low income sectors, this could increase the incidence of poverty.





¹⁶ For more details see Appendix A.



Figure 7. National loss of productive labour is driven by decreased productivity among agricultural workers in most countries

Notes:Bars indicate the share of total national labour productivity losses among workers in individual sectors.Source:Vivid Economics

Seasonal impacts are an important consideration – with India losing almost no hours due to high temperature in December and January, but losing almost half its working hours during May and June. Figure 8 shows the relative importance of seasonality in India and Jordan – where the incidence of very high temperatures is concentrated in a few months of the year, compared to Ghana, Ethiopia and Tanzania – where the loss of effective work hours is relatively evenly spread across the year.

Figure 8. Heat increase impacts on labour productivity will be particularly severe between April and July in India, but will have more constant but lower level effects throughout the year in Ghana



Source: Vivid Economics

4.3 Economic impacts of temperature increases

Under today's economic conditions, the increase in temperatures expected by 2050 would lead to substantial further economic losses, particularly in countries already exposed to high temperatures and losses today. Figure 9 shows the impact on today's economy under the temperatures expected in 2030





and 2050. If nothing changed in the five case study countries' economies except the temperature levels – that is, if there were no changes to the number of workers or to the capital stock – the impact of increased temperatures by 2050 would be a further GVA reduction of 0.2 percentage points in Jordan (up to 0.5 per cent of GVA from 0.3 per cent of GVA today), or a further 0.8 percentage points in Tanzania – a large proportional increase from a GVA loss of just 0.7 per cent today. The hottest countries today – Ghana and India – see the greatest absolute increases in economic losses, as more hours are exposed to increasingly hot temperatures.

Losses associated with turn of the century temperatures are an important part of the overall losses – as shown by the green bars in Figure 9. The green 'baseline' bar includes both the impact of already high temperatures, and the impacts of rising temperatures due to climate change at the turn of the century; global temperature increased by around 1.1°C between the mid-late nineteenth century average temperature (1850-1900) and 2015.¹⁷





Source: Vivid Economics

However, economic growth means that the economy in 2050 will not look like today's economy; with the impacts presented in Figure 10. As set out in Section 3, a simple stylised pathway growth in economic output is modelled for each country, based on growth in the size of the labour force and accumulation of capital. As capital is expected to grow faster than labour between now and 2050, the capital stock is expected to contribute <u>relatively</u> more to GVA than labour in each sector's production function, so the GVA share associated with each worker is lower. In Section 9.2, we consider the further case where the economy transitions to different shares of activity in different sectors.





¹⁷ Based on latest data available from the UK Met Office Hadley Centre for Climate Science and Services(Met Office, 2017).

Given these stylised growth pathways for each country, future losses as a share of GVA decrease relative to the constant economy depicted above. Economic losses accounting for this stylised economic growth range from a high of 3.6 per cent in Ghana to a low of 0.3 per cent in Jordan in 2050, as shown in Figure 10. While losses as a share of total GVA are falling over time, losses in absolute terms increase substantially; absolute losses in 2050 range from three times (in India) to nine times (in Ethiopia) the value of 2015 GVA losses.

These economic costs are similar to the results from previous analysis of high temperature impacts on labour productivity. For example, the 2050 damages in the range of 0.3 per cent to 3.6 per cent of GVA are close to or within the range of damages estimated at the city level by Costa, Floater, Hooyberghs, Verbeke, & De Ridder (2016), where damages in Antwerp, Bilbao and London (in 2100) range between 0.4 per cent and 9.5 per cent of GVA.





Source: Vivid Economics

While total GVA losses due to high temperatures increase in some countries and decrease in others, the proportion of losses due to additional temperature increases is increasing over time. Figure 11 decomposes the aggregate future GVA losses into the shares due to current climate conditions, and to future temperature increases. While turn of the century temperatures are already high enough to account for the majority of the economic losses in all countries in 2030, by 2050, future temperature increases account for more than half of the estimated GVA losses for Ethiopia, Jordan, and Tanzania. That is to say, without future climate change, labour productivity damages would be less than half as large as projected in 2050 in Ethiopia, Jordan and Tanzania, and around three quarters as large in Ghana and four-fifths as large in India.







Figure 11. Future economic losses due to current and future climate conditions



Similar to the distribution of labour productivity losses across sectors, in Ethiopia and Tanzania around four fifths of the economic losses are concentrated in the agriculture sector, whereas in India and Jordan the losses are more evenly distributed throughout sectors of the economy (Figure 12). This makes sense, as Ethiopia and Tanzania have the largest shares of the workforce employed in the agriculture sector (73 per cent and 67 per cent respectively). However, while half of India's employment is in Agriculture, this falls to just 2 per cent for Jordan. Ghana, which has a lower share of workforce employed in agriculture, sees a greater proportional drop in GVA than India in this sector.¹⁸ However, sectoral GVA losses also reflect the relative productivity levels of workers in different sectors. For example, the share GVA losses from agriculture is smaller than the share of overall productivity lost from agriculture in Ethiopia and Tanzania, reflecting the fact that agriculture is relatively less productive per worker than construction. In contrast, Jordan's agriculture sector delivers a high level of GVA per person, so the share of GVA losses from agriculture is greater than the share of lost productive time.



¹⁸Table 13 in Appendix A presents summary statistics for each of the case study countries.



Figure 12. Distribution of losses in 2050 by sector of the economy



Moving to a climate change scenario with a greater expected increase in temperature by 2050 increases expected GVA losses by about a further 0.2 to 0.5 percentage points in each country. This is shown in the left panel of Figure 13, by the red bar above the base blue scenario, where temperature increases in 2050 average 0.4°C to 0.7°C above the average values used in the base case average of all scenarios. Similarly, in a world where climate change impacts were less severe than expected (0.3°C to 0.4° C lower than in the base case), the impact on GVA would be correspondingly lower – of the order of 0.1 to 0.4 percentage points – as shown by the green bars on the right panel of Figure 13.







The relatively modest change in impacts across the climate scenarios used is a result of relatively little dispersion in expected temperatures by 2050. Beyond 2050, where uncertainty on climate change impacts









Using alternative formulations of the heat-productivity relationship could more than double the estimates of labour productivity and GVA loss in 2050. Figure 15 shows the additional GVA loss in 2050 from applying the ISO standards for labour productivity loss instead of the Hothaps relationships, with GVA losses increasing by between 0.4 percentage points and 3.6 percentage points, with overall losses increasing by between 90 per cent and 113 per cent relative to the base scenario using the Hothaps relationships. This reflects increases in the labour productivity loss itself of between 1.5 percentage points and 10.8 percentage points (with relative increases ranging from 55 per cent to 108 per cent). However, as noted in Section 2.3, the ISO standards reflect their goal of safeguarding workers against negative impacts by suggesting very rapid withdrawal of labour as temperatures increase to avoid health impacts for most workers. Applying the ISO formulation of the relationship is likely to therefore overestimate the actual impact of high temperatures on labour productivity.







Figure 15. Using the ISO heat:productivity relationship increases the modelled GVA losses substantially in all countries

Across all scenarios presented, the impacts should be seen as a lower bound, as they are based on 12 representative monthly days with fitted within day temperature profiles. In reality, there will be a distribution of temperatures within each month, which is masked by the implicit average representative monthly days used here. Furthermore, we may expect temperature volatility to increase in the future – not just increase on average. Allowing for these variation and volatility effects would push temperatures more often into the extremes of the range – and increase the number and extent of hours exposed to WBGT above 26 degrees, and therefore would increase labour productivity and associated GVA losses.



Source: Vivid Economics

5 Contextualising the Scale of Impact

This section provides a high-level review and comparison of literature on other economic impacts of climate change, and other factors that affect labour productivity. The review of literature on each of these two impact mechanisms provides context for the modelling results presented in Section 4.

5.1 Other climate change impacts

Climate change will impact on people, and workers in particular, in developing countries in many ways. In addition to the other direct health impacts from temperature increases noted above in Section 2.3, the International Labour Organisation notes that climate change is likely to affect labour forces and the broader international Sustainable Development Goals (SDGs) (UNDP, 2016).

The ILO identifies a number of ways in which increasing temperatures are likely to impact on the achievement of the SDGs, though it does not provide an estimate of the economic costs associated with each of these:

- increasing poverty particularly among agriculture sector workers;
- increasing hunger among small-scale and subsistence farmers;
- affecting education and learning through heat exposure;
- exposing individuals to health risks and increased heat strain;
- impacting gender equality due to high exposure of occupations involving large proportions of women;
- making it difficult to meet international standards for work safety;
- increasing inequality through more severe impacts in poorer regions; and
- challenging the achievement of sustainable cities due to more intense heatwaves in urban zones.

In addition to these impacts on workers from rising temperatures, there is a much broader range of climate impacts. Projected climate impacts include changes in precipitation and weather patterns, changing incidence and severity of extreme weather events, sea level rise, and changes in human activities in response to climate change, such as tourism patterns and expenditure on energy for cooling and heating. High temperatures are also associated with increased long-term migration due to negative impacts on income (Mueller, Gray, & Kosec, 2014).

A small number of studies have directly compared costs associated with heat-related labour productivity loss with the costs from other climate impacts. These studies suggest that the labour-productivity impacts are likely to be significant and on a level with or greater than a number of other impacts – though not all impact channels, and relative costs of different channels are likely to vary across different countries and socio-economic and environmental contexts.

The 2011 ClimateCost project exploring the economic cost of different climate impacts for European countries finds that labour productivity impacts are likely to be in a similar range to - and in some cases costlier than – other impacts. The analysis values productivity losses from temperature increases in Europe in the range of €300 million to €740 million per year by the 2080s under a medium-high emissions




scenario (S. Kovats et al., 2011), while increased mortality due to coastal flooding is expected to lead to costs of around \notin 750 million per year in the 2080s, with costs from increased food borne disease expected to reach up to \notin 89 million per year in welfare costs.

However, the ClimateCost study estimates costs for heat-related mortality substantially greater than other climate impacts, reaching up to \in 147 billion per year in the 2080s, though this finding is sensitive to the method used to value a statistical life and could be an order of magnitude lower under alternative measures.

Similar analysis by Ciscar et al. (2014) identifies that labour productivity impacts are projected to be substantial across Europe and dominate other health effects of climate change, though the analysis does not separate the aggregate health impact into the various sub-channels of costs it considers (hours of labour lost due to morbidity and mortality, additional health expenditures, reduced labour productivity due to warmer temperatures, and increased mortality).

Roson and Sartori find that the expected impact of climate change related heat increases are largest in the tourism sector, followed by labour productivity impacts (Roson & Sartori, 2016). The study estimates economic damages for each of the 140 countries in the GTAP9 dataset under a simulated 3°C for six different climate change impacts:(i) labour productivity loss, (ii) sea level rise, (iii) agricultural productivity, (iv) human health, and (v) tourism flows. For example, the study finds that:

- Tourist and associated currency flows has potentially the biggest overall impact on aggregate GDP: and is the most important of the five impact mechanisms in half of the countries;
- Reduced labour productivity is the second largest impact in aggregate, and is the single largest cost in a quarter of the countries.
- For the five countries included in this analysis, the study finds that heat impacts on labour productivity are projected to be the largest impact channel in Ghana and India (reducing GDP by around 7.6 per cent and 3.3 per cent respectively), accounting for over half of expected damages from the five channels. Tourism effects dominate in Jordan and Tanzania, and agricultural productivity effects in Ethiopia. Labour productivity impacts are projected to account for around 16 per cent of the total impacts in Tanzania, and a smaller share of impacts in Jordan and Ethiopia.

Studies of the total costs of climate change in comparable contexts to the five countries case studies in this analysis estimate a GDP loss of c. 1.5 per cent per °C temperature increase. For example, Dell et al., 2012 identify a 1.4 per cent loss of GDP in poor countries per 1°C increase in temperatures. Analysis by Burke et al., 2015 estimates a global reduction in GDP per capita of 23 per cent by 2100 due to temperature increases. Similarly, a review of climate studies from the period 1994 to 2013 suggests that temperature increases in the order of 2.5°C to 3°C are likely to lead to total damages equivalent to 0 per cent to 4.8 per cent of GDP (Tol, 2009, 2014).

The Intergovernmental Panel on Climate Change (IPCC) notes that temperature increases of the order of 2°C are likely to lead to losses equivalent to 0 per cent to 2 per cent of GDP (IPCC, 2014). Recent modelling by the OECD (2015) also identifies global average costs of 2 per cent of GDP by 2060 due





to climate change, though this is not evenly dispersed across regions. For example, India is expected to see a 4.3 per cent loss in GDP, while Southern Africa, North Africa and other African countries are projected to experience GDP losses of 2.2 per cent, 3.5 per cent and 4.1 per cent respectively, while the Middle East is expected to experience losses of 3.2 per cent of GDP.

The OECD also decompose these overall costs into different impact channels, as shown in Table 4. These estimates include a number of climate change impact channels, although none include estimates of labour productivity loss due to higher temperatures. This implies that the inclusion of the effects of higher temperatures on labour productivity could substantially increase the economic costs from climate change, potentially doubling damage estimates in some regions.

Table 4.Health and agriculture impact channels in particular are projected to lead to significant costs for
African countries, the Middle East and India

Region / Country	Impact channel								
	Agriculture	Coastal zones	Energy demand	Extreme events	Health	Tourism demand			
Southern Africa	0.2%	0.0%	0.0%	0.0%	1.8%	0.2%	2.2%		
North Africa	1.6%	0.0%	0.1%	0.0%	1.5%	0.4%	3.5%		
Other Africa	0.5%	0.8%	0.0%	0.0%	1.7%	0.3%	3.2%		
India	2.7%	0.5%	0.0%	0.0%	1.2%	0.0%	4.3%		
Middle East	0.7%	0.5%	0.0%	0.0%	1.5%	0.5%	3.2%		

Note: 'Agriculture' indicates changes to crop yields, fisheries catches and pasture and rangeland productivity; 'Coastal zones' indicates loss of land and capital from sea level rise; 'Energy demand' indicates changes in demand for cooling and heating; 'Extreme events' indicates mortality, land and capital damages from hurricanes and floods; 'Health' indicates mortality and morbidity from heat exposure, infectious diseases, and cardiovascular and respiratory diseases; 'Tourism demand' indicates changes in tourism flows and services.
 Source: OECD (2015)

National studies and strategies identify costs of climate change or weather events for some countries.

The nationally determined contributions (NDCs) often identify the expected costs of climate change, although do not go into detail on the specific effect of heat on labour productivity:

- India's first NDC document notes that India is likely to experience overall climate damages of around 1.8 per cent of GDP by 2050, associated with temperature increases of just over 2°C (Ahmed & Suphachalasai, 2014; Government of India, 2015).
- Tanzania's NDC identifies that current climatic and extreme weather events lead to costs in excess of 1 per cent of GDP (United Republic of Tanzania, 2015). Separate modelling for Tanzania has estimated that total costs of climate change could be on the order of 1.5 per cent to 2 per cent of GDP by 2030 (P. Watkiss, Downing, Dyszynski, Pye et al., 2011).





 Ethiopia's, Ghana's and Jordan's equivalent documents do not include equivalent assessments of economic costs associated with current or future climate conditions.

There are a number of important caveats to be made in interpreting quantitative estimates of the costs of climate change from diverse sources. In general, models rely by necessity on strong, and often disputed, assumptions. For example, the value that society places on lost consumption due to climate change, or the sensitivity of the relationships between emissions and temperature, and between temperature and other climatic changes (Pindyck, 2013). Furthermore models often do not include impacts of climate change on GDP growth, as opposed to shocks on annual GDP levels (Stern, 2013), which could lead to substantial increases in cost estimates. As noted in Section 2.2, Dietz & Stern (2015) estimate that by 2200 consumption per capita could be 11 per cent to 24 per cent lower when climate change impacts drivers of growth than under standard modelling, depending on how climate change affects the drivers of growth.

Overall, the evidence suggests that heat impacts on labour productivity are an important impact mechanism of climate change relative to other impact channels, even under moderate climate change scenarios. While some studies find the cost of human life associated with climate change is the overwhelmingly dominant cost, and others find important losses associated with specific sectors, the literature consistently highlights important labour productivity losses associated with heat impacts.

5.2 Non-heat related impacts on labour productivity

In this section we provide context for the heat impacts on labour productivity, by a review of evidence on other channels that affect labour productivity. In particular, we discuss relative importance of health impacts on labour productivity, and of education for productivity and for human capital accumulation.

5.2.1 Literature on the impacts of health on productivity

Health economics literature provides an estimate of the economic costs of disease, including through impacts on labour productivity. Health research and health economics studies have explored both the individual-level productivity effects of varying diseases, and the broader economic costs of these productivity impacts.

The health literature often splits productivity impacts into two effects: 'absenteeism' and

'presenteeism'. *'Absenteeism'* is interpreted as a physical absence from the workplace, while *'presenteeism'* represents reduced effectiveness while at work. This framework is similar to the three channels for heat-related productivity loss described in Section 3: reduced labour inputs, reduced effort during work task, and reduced effectiveness during tasks.

The impact of malaria on labour productivity and economic outcomes is substantial. Experimental evidence from agricultural workers in Nigeria finds that anti-malarial treatment increases labour supply by around 10 per cent in the weeks following treatment (Dillon, Friedman, & Serneels, 2014). A meta-analysis of various studies finds overwhelming evidence of the impact of malaria on productivity at the individual level, though indicates wide ranges in the estimated days of work 'missed', from 1 to 16 days per malaria episode (Asenso-Okyere, Asante, Tarekegn, & Andam, 2011). Comparing outcomes across the studies is





challenging, as different methodologies are used and the studies assume that the costs of malaria are equivalent to the avoided losses from effective malaria prevention (Asenso-Okyere et al., 2011). In terms of long-term impact, countries with 'substantial' levels of malaria grew by c. 1.3 per cent less per year, and a 10 per cent reduction in malaria is associated with 0.3 per cent higher growth per year (Asenso-Okyere et al., 2011).

National-level studies identify productivity losses across illnesses / classes of health impairments. For example:

- Evans-Lacko & Knapp (2016) find that annual costs associated with absenteeism and presenteeism due to depression – based on self-reported conditions – are equivalent to 3.5 per cent of GDP in Brazil, 0.5 per cent in Canada, 0.2 per cent in China, 0.3 per cent in Japan, 0.1 per cent in Korea, 1.2 per cent in Mexico, 4.9 per cent in South Africa and 0.5 per cent in the USA, with presenteeism representing the majority of costs in all countries.
- Stewart, Ricci, Chee, & Morganstein (2003) identify overall hours of work lost per employee per week for 'personal or family health reasons' in the American Productivity Survey, finding that the average worker loses 1.99 hours per week due to health reasons, of which 0.67 hours is due to absence from work and 1.32 hours is due to reduced performance while at work. Assuming a 40 hour work week, these values equate to roughly 5 per cent loss in working hours on average.
- Oliva-Moreno (2012) estimates that the loss in labour productivity due to accidents and health problems in Spain was equivalent in size to 4.2 per cent of GDP in 2005.

A number of studies present individual estimates of health-related productivity implications of individual disease vectors in other contexts. Goetzel et al. (2004) examine individual prevalence and impairment rates for the top 10 most prevalent health conditions affecting United States employers, finding that the most common health conditions lead to significant lost productivity through absenteeism and presenteeism, as shown in Table 5. These impacts represent expected aggregate productivity losses at a national level and so represent a combination of both prevalence of the disease vector and impact on the individual. It is perhaps not surprising therefore that the largest productivity losses are associated with relatively prevalent diseases.

The impacts of high temperatures on labour productivity may be larger than productivity impacts from many of the most common disease vectors. Four of the 10 most common disease vectors: cancer, diabetes, heart disease and hypertension, have productivity impacts below 1 per cent, the smallest impact projected due to temperature increases by 2050. Only one disease vector – migraines, with the largest associated national productivity loss at 6.4 per cent-leads to losses that exceed the 5 per cent maximum 2050 productivity losses projected for the case study countries.





Table 5.The aggregate impacts of the top 10 most prevalent US diseases ranges between 0.3% and 6.4%
productivity loss

Disease	Prevalence rate	Productivity loss due to absenteeism among those with the condition	Productivity loss due to presenteeism among those with the condition	National productivity loss due to absenteeism among the total population	National productivity loss due to presenteeism among the total population	Total national productivity loss
Allergy	25.8%	3.4%	10.9%	0.9%	2.8%	3.7%
Arthritis	12.4%	2.5%	11.2%	0.3%	1.4%	1.7%
Asthma	8.3%	5.0%	11.0%	0.4%	0.9%	1.3%
Any cancer	2.0%	7.0%	8.5%	0.1%	0.2%	0.3%
Depression/sa dness/mental illness	13.2%	10.7%	15.3%	1.4%	2.0%	3.4%
Diabetes	3.9%	0.8%	11.4%	0.0%	0.4%	0.5%
Heart disease	6.4%	2.8%	6.8%	0.2%	0.4%	0.6%
Hypertension	12.4%	0.4%	6.9%	0.05%	0.9%	0.9%
Migraine/head ache	25.6%	4.5%	20.5%	1.2%	5.2%	6.4%
Respiratory disorders	10.9%	6.1%	17.2%	0.7%	1.9%	2.5%

Source: Goetzel et al. (2004)

5.2.2 Literature on the relationships between heat, education and productivity

Education and skills are associated with higher earnings – and improved productivity. A better educated workforce would be expected to be more productive and to contribute more to economic output.

There is good evidence on the impact of education on rates of growth, but limited comparable evidence of impacts of education on contemporaneous output or task-based labour productivity. Analysis of international datasets indicates that increased quantity of schooling and quality of education are both associated with high rates of long-run economic growth (Hanushek & Woessmann, 2007). Higher quality education is also associated with increased wages, potentially reflecting increased individual productivity compared to those with lower quality education. However, the impacts of education are commonly formulated as impacts on long-run growth rates; there is limited evidence of how different levels of education are associated with different levels of individual worker productivity or aggregate levels of economic output. Nonetheless, simulation-based evidence on the aggregate impacts of these changes to growth rates suggests that an educational reform that increased educational quality by a 0.5 standard deviation above the mean over 20 to 30 years would lead to increased levels of GDP of the order of 5 per cent of GDP after 35 years, equivalent to the time frame considered in this analysis (Hanushek & Woessmann, 2007).



However, high temperatures may be associated with poorer educational outcomes. This will have an impact in the short term on educational attainment, and in the longer term through human capital accumulation, which may affect both the level of and growth in economic output.

For example, in the US, high temperatures on the exam days increases the likelihood of failing the examination, with reduced performance on a hot day in New York schools (32°C versus 22°C) being equivalent to 15 per cent of a standard deviation in test scores, or about one quarter of the average gap observed between black and white students (Park, 2017).

Persistent exposure to high temperatures over the course of a school year can reduce the likelihood of graduating on schedule by just over 3 percentage points for an increase of just over 2°C, and can reduce the rate of learning, with a one standard deviation (3.91 days) increase in the number of days with maximum temperatures above 27°C having an impact equivalent to half of the impact of reducing class size from 31 to 25 (Park, 2017).

The education effects would mostly affect longer-term growth rates, and are not directly comparable to the task-based reduction of labour productivity estimated in this study. The impact of temperatures on the accumulation of human capital is one of the potential ways in which climate change could reduce economic growth.





PART B

Adapting to higher temperatures to mitigate labour productivity losses

:vivideconomics





6 Adapting to Heat Impacts on Labour Productivity

PART A estimated the potential impact of heat increases on labour productivity and showed that this is important both in absolute terms and relative to other impacts of climate change. Across five case study countries: Ethiopia, Ghana, India, Jordan and Tanzania, we found that the potential impact of high temperatures would result in an estimated loss of productivity equivalent to losing up to 20 per cent of the labour force (in India), or up to 3.6 per cent of GVA (in Ghana) by 2050.¹⁹

In the following sections we set out ways in which countries could adapt to mitigate these productivity losses identified. First, we map the solution space of adaptation options, and select a shortlist for more detailed analysis. Finally, we provide a discussion of how different adaptation measures will be most appropriate from a value for money perspective in different contexts and different trends.

The appropriate mix of adaptation measures will be highly context specific. There is relatively little literature and evidence on the implementation of adaptation measures in different geographical contexts. We have drawn on the best available evidence and independent data sources to describe how the contextual factors would be relevant to each country. While the optimal adaptation solutions would need to be considered through more detailed technical and economic studies, we provide initial evidence on the circumstances under which measures are likely to be most cost-effective.

A series of indicative case studies are used to illustrate how contextual factors determine the appropriate adaptation measures in different countries and regions. The case studies consider a particular technology in more detail, and describe how the measure could be implemented in different contexts, its likely impact, and which contextual factors will determine when / how much the measure should be used.

¹⁹ Gross value added (GVA) and gross domestic product (GDP) are both measures of national economic output and are broadly comparable. GDP is measured as GVA (production output at current prices), plus taxes on production, minus subsidies to production.





7 Mapping Adaptation Options

There are a wide range of adaptation options that can mitigate the impacts of increased temperature on labour productivity. We identify measures that could mitigate the impact channels identified in Section 2.3.2, namely: (i) a decrease in the supply of labour (total hours worked), (ii) a reduction in the effort applied per hour worked, (iii) a reduction in productivity, per hour worked, for a given level of effort. We do not distinguish between how adaptation measures affect each of these three mechanisms, but focus on the aggregate relationship between temperature and productivity losses. A longlist of measures identified is presented in Appendix E.

We map the universe of potential adaptation measures using four factors. This mapping is intended to provide a framework for considering how different measures operate, and is also used to develop a shortlist of options to assess in more detail within the scope of this study. The four factors considered are:

- <u>type of response</u>: We classify measures as 'technical', 'regulatory and policy', 'behavioural', or 'research and development'. Technical measures are for example engineering responses to cool workspaces, such as air conditioning, or green roofs where a building roof is fully or partially covered in soil and vegetation. Regulatory and policy measures are about building design standards, 'green' design, or increasing urban greenspace, or promotion of particular technologies. Behavioural responses operate at individual or firm level, and include changing working hours, locations, or employment type. R&D measures refer to pilot programmes and research to improve effectiveness adaptation measures or develop new adaptation options.
- primary agent of change: To understand the implications for policy, we consider whether the main driver
 of uptake of the measure is individuals, the private sector, or government.
- <u>feasibility of implementing the measure</u>: Based on an initial review of the literature and expert input, we consider the likely feasibility of implementing adaptation options at the scale needed to reduce the significant potential impact of high temperatures on labour productivity. While the 'economic' feasibility will be a function of cost, in this case we refer more to other potential barriers to wide-scale implementation. For example while 'assisted migration' away from hot areas could be attractive from the perspective of reducing productivity losses, and the 'direct' economic costs (discussed in section 8.1) may not appear large, the social implications of doing this only on the basis of productivity losses make it hard to envisage as a feasible large scale solution.
- potential scale of impact: Based on an initial review of the literature and expert input, we consider what
 the scale of potential implementation is for each measure; for example, some measures might be very
 effective but with a more limited possibility for use as a wide-scale solution.

There is a high degree of correlation between the type of response and the primary agent of change, as set out in Figure 16. Some responses could arguably fall across typologies; for example design options fall partly under policy, and partly under technical solutions. For the most part, technical responses fall largely





on firms for implementation; regulatory and policy and R&D are more driven by government; and behavioural responses would be driven primarily by individuals and companies. While this maps the 'primary' agent of change, other stakeholders may have an important role to play; taking the example of behavioural change, government could be instrumental in creating an environment or regulations that facilitate change in norms.



There is a relatively high degree of correlation between the type of measure and the primary agent of Figure 16.

Source: Vivid Economics -details per measure in Appendix F

From these selection criteria, we identify 17 measures for detailed analysis. The main determinants of measures included in this shortlist were qualitative assessments of feasibility and potential impact, and ensuring a reasonable coverage of measures across type and primary agent of change. This selection is set

low feasibility, yellow indicates medium feasibility, green indicates high feasibility. (3) Bold typeface indicates measures included in the shortlist for this analysis.





out in Appendix E, and is based on a review of literature as set out in the References section at the end of this report.



8 Evaluation Framework for Adaptation Options

8.1 Direct and indirect costs and benefits

To evaluate the potential cost-effectiveness of the adaptation options, we develop a set of criteria to assess cost-effectiveness and value for money (VfM). This framework sets out the range of economic, environmental and social costs and benefits associated with each option, and contextual factors that will determine the relative magnitudes of these costs and benefits across different circumstances.

Cost-effectiveness cannot be considered in isolation from context. Cost effectiveness and VfM should be considered through an assessment of all direct and indirect costs and benefits, not just the direct impacts. Importantly, the relative importance of the full range of costs and benefits will be highly dependent on context, so a 'general' approach to assessing for cost-effectiveness is not appropriate. We set out these contextual factors in Section 8.2, and provide worked examples through case study boxes in Section 9.2.

The direct economic costs of each adaptation measure include direct financial costs, and a range of 'indirect' costs. The direct financial costs include the capital investment costs required to install technology – this is a one-off up-front cost – and variable costs associated with maintaining and using equipment, and the replacement cost as assets depreciate over their economic lifetime.

The direct economic benefits are the direct impact of avoided productivity losses, considered in terms of the expected impact of a reduction in temperature for workers delivered by each option.

We also consider a range of co-benefits and indirect costs, which include for example health benefits and indirect impacts on, for instance, climate change mitigation. For both indirect costs and co-benefits we consider: climate change – efforts to mitigate or adapt to the impacts of climate change; environmental – impacts on the natural environment, such as biodiversity, water quality; socioeconomic – including job creation, education, leisure and amenities; health – impact on pollution, accidents, and other biophysical responses to increased temperatures.

Table 6 summarises the types of cost and benefit associated with adaptation measures. Details on the extent of each of these costs and benefits for each measure are provided in Appendix F.





Table 6. Direct and indirect costs and benefit categories and descriptions

Direct ben	efits	Direct costs				
• boo pro	dy temperature reductions reduce labour oductivity losses	 variable capital maintenance costs variable operational costs variable capital maintenance costs 				
	Co-benefits an	d indirect costs				
	Climate: • increases or reductions in GHG • increases or reductions in adapt	emissions ive capacity or vulnerability				
\$ 22	 Socioeconomic: potential impact on employment levels and the way of work – such as the social costs of changing working days and/or hours impacts on social outcomes such as use of leisure time, education 					
	 Environmental: changes to the environment beyond climate issues for example, increased biodiversity, increased water use, increased pollution 					
	 Health: impacts of reduced thermal disc elderly, accident risk, respiratory broader impacts from options, set 	omfort on human health outcomes – such as on the problems, and so on uch as reduced health effects from pollution				

Source: Vivid Economics

8.2 Contextual factors and uncertainty

The adaptation measures aim to reduce the impact of future temperature increases, in future states of the world. These temperature increases and other contextual factors by 2030 or 2050 are unknown and in some cases may be highly uncertain. The implication of these uncertainties is that while one set of responses might turn out to be appropriate with the benefit of hindsight for a particular state of the world in 2050, an altogether different set of responses might be different if the uncertainties unfold differently between now and 2050. The effectiveness of choices we make today will depend on how these uncertainties unfold, and some responses may have better properties in the face of uncertainty:

- <u>'No' (or 'low') regrets</u>. Measures that deliver a net positive socio-economic value in all future states of the world can be described as 'no-regrets' measures. That is to say that across all possible outcomes for all uncertainties (for example climate change) the present value of socio-economic benefits is greater than the present value of costs. So whatever happens tomorrow, people will not regret making the investment today. The no-regrets concept can be particularly useful when deciding which investments to prioritise in the short term; specifically, they allow investment early rather than 'wait and see'.





- <u>Flexibility</u>. Some investments may increase ability to adapt to uncertainties as they evolve, as information regarding uncertainties is revealed over time. For example, 'modular' options can be scaled up over time, while others may involve large, irreversible, up-front costs – creating a 'lock-in' to a particular response type. Other investments may increase flexibility by improving understanding of uncertainties over time (for instance the value of pilot schemes and of R&D), or where they are a complementary to other types of investment. Under a 'real options' lens, it can make sense to invest in options that increase flexibility – even if they are not eventually implemented, until more information on uncertainties is revealed.

The relative balance of these costs and benefits will differ by the context in which it will be applied. Key factors that will influence the interaction of costs and benefits in different regions and contexts include:

- <u>Indoor vs outdoor</u>. While some measures to address high temperature impacts on labour productivity are applicable across all workers in an economy, across all sectors and work environments, others are specific to certain types of environments, or are more effective in certain environments. For example, shifted working hours can be applied across all sectors, but might be particularly effective for outdoor workers that are exposed to intense direct sunlight during the hottest period of the day. Alternative, measures like air conditioning, increased ventilation or window shades would only be applicable to indoor workers.
- <u>Urban vs rural.</u> Reducing heat stress on workers will be very different in a densely populated urban setting compared to a dispersed rural environment. In major urban centres, there will also be a *'heat island'* effect, which raises temperatures further. In rural settings, electricity grid and generating infrastructure may be weaker, and the workforce predominantly outdoors, which will imply a different set of solutions than would be appropriate in major urban centres.
- <u>Temperature profiles base and peak.</u> While some measures will reduce indoor temperatures all the time, others may be most effective in dealing with temperature volatility. The most cost-effective solution mix will be different in a setting of high, but low volatility, temperatures, compared to one of lower average, but higher volatility temperature.
- Energy costs and carbon intensity of energy. To the extent that adaptation measures require electricity generation, the cost of electricity, and the associated carbon emissions, would impact its cost-effectiveness, and thus the applicability of measures to different contexts. For example, air conditioning (AC) may be appropriate in situations where energy is low cost and the emissions intensity of the electricity grid is low, potentially due to large scale hydropower or, for example, cost-effective solar PV and/or storage. On the other hand, AC will be less appropriate where electricity costs are high and/or the grid intensity is high due to substantial fossil-fuel generation or inefficient transmission and distribution, or where increased usage could affect quality of service (for example blackouts).

The assessment of applicability in different contexts is intended to allow practitioners to identify adaptation measures that would be cost-effective in different contexts. Policy makers can identify subsets of measures that are relevant to the contexts they are working in, and identify the most suitable options from within this subset, through considering whether and how the individual contextual factors apply to the situation under consideration.





9 Assessment of Adaptation Options

9.1 Assessment of the shortlist

For each shortlisted option we undertake a qualitative assessment of the relative merits and challenges for implementation of each. A qualitative scoring of direct and indirect costs and benefits, and the relative importance of uncertainty and contextual factors is presented in Table 7. The scoring is based on review of available literature (often limited), and expert opinion. More details on the attributes of each measure are provided in Appendix F.

The left panel of Table 7summarises the relative costs and benefits (both direct and indirect). This sets out the relative importance of each of the direct and indirect costs and benefits for each adaptation option in the form of a heatmap; the stronger the shade of green for the benefits, the greater these expected benefits are expected to be under most circumstances. Similarly, the stronger the shade of red, the more important these costs are expected to be.

While the balance of costs and benefits will be heavily dependent on local markets and contexts, the bullets below present some illustrative examples:

- Air conditioning can be very effective at reducing working temperatures (for indoor workers), as with the appropriate technology, one could potentially reduce temperatures to below the 25 WBGT threshold from any (high) starting point. Other options, such as shades and green roofs may have a more limited range of impact. Passive cooling measures may be as effective, but only in the appropriate circumstances (for example within a particular temperature range, or requiring informed behavioural response).
- Green roofs, while less effective at reducing temperatures in all contexts, bring potentially large cobenefits in terms of improving the quality of the built environment, reducing health problems associated with particulate matter, and reducing noise pollution, and so on.
- Some options may appear relatively low benefit, but may be relatively low cost, such as outdoor shades, or individual heat cooling measures which come at very low cost.

The costs and benefits cannot be considered in isolation from the context in which the measure would be implemented. A particular measure might be expected to be effective at reducing heat stress on workers – and therefore mitigating productivity losses – in 'average' conditions, but might be much less effective in a specific setting. For example, a measure that requires a large consumption of electricity might be appropriate in settings where the cost of power generation and transmission is low, but less so where there are constraints to electricity access or consumption.

The relative importance of uncertainty and contextual factors is summarised in the right panel of Table 7. The light yellow shade indicates that a measure performs relatively poorly in a particular context. The darker the shade of blue, the better suited a measure is for the contextual factor in terms of potential to reduce temperatures. For example:





- Air conditioning can reduce high base temperatures, and can respond flexibly to reduce high peak
 temperatures. This ability to respond quickly to variation in temperatures differentiates it from many of
 the other options. However, it performs relatively less well where the (incremental) cost of electricity
 generation is high, or where the carbon intensity of electricity production is high, or where access to
 electricity is low and increasing AC would not be feasible (or be prohibitively expensive), or would result
 in increased risk of blackouts.
- Shading options and other passive design options, such as green roofs (or spatial zoning on the longlist) may be more cost-effective than technical solutions.
- Green roofs are most appropriate in densely populated settings, where they can potentially reduce the urban heat island effect.
- Changing working hours could be very effective in sectors where high-intensity, outdoor working is
 common. These areas may also coincide with regions where the daily temperature differential is large, so
 the potential for mitigating productivity losses by avoiding the hottest parts of the day can be large.





Table 7. Appraisal summary table – summary of costs and benefits

#	Adaptation response	Direct benefits		Co-be	nefits		Direct	costs		Indired	t costs		Unce	rtainty	Contextual factors							
		Reduced productivity loss	Climate	Socio-economic	Environmental	Health	Fixed costs	Variable costs	Climate	Socio-conomic	Environmental	Health	Low-regrets	Flexibility	Indoor	Outdoor	Urban	Rural	High base temperature	High peak temperature	High energy costs	Carbon-intensive energy
Techn	Technical adaptation measures																					
1	Air conditioning																					
2	Increased ventilation																					
3	External shading																					
4	Internal shading																					
5	Reduced internal gains																					
6	Increased albedo																					
7	Green roofs																					
8	Mechanisation																					
9	Outdoor shade																					
Infras	tructural, planning and regulatory adaptation	measures																				
10	Climate smart municipal design																					
11	Structural economic shifts																					
12	Early heat warning stations																					
13	Education and awareness campaigns																					
14	Worker practice & monitoring programs																					
Behav	ioural adaptation measures																					
15	Occupational choice																					
16	Changing working hours																					
17	Individual heat-reducting activities																					
			strong be	nefit		ļ		strong co	st					strong in	context			weak in c	ontext			

Note: Costs and benefits are ranked on a four-point scale: none (blank), low (light shading), moderate (medium shading), high (dark shading).

Contextual factors are ranked on a four-point scale: weak in context (beige shading), neutral in context (blank), good in context (light shading), strong in context (dark shading)

Source: Vivid Economics



9.2 Trends and case study examples

In deciding on which adaptation measures to support, policy makers need to consider key contexts and uncertainties that affect the effectiveness of options, in addition to baseline costs and benefits. In

particular, the following questions should be asked in considering the appropriate policy mix to mitigate the impact of heat on labour productivity:

- are there barriers to autonomous take up by individuals and firms that mean that in the absence of policy intervention the measure will not be adopted to the optimal extent?
- how does this measure interact with other measures to reduce the impact of heat on labour productivity?
- does the measure complement, overlap with, or work against other (non-adaptation) policies?
- what would be the cost of removing the barriers that currently restrict optimal adoption of the measure?
- how suitable are proposed measures for different climate scenarios and how easily can they be adjusted as the climate evolves?
- how quickly can the measure be scaled up?
- how are different cost, benefit, uncertainty and contextual factors expected to evolve (for example are financing constraints temporary)?

To give an example, shifting working hours may not happen automatically as individuals and firms tend to work the same hours across the supply chain. While shifting working hours is theoretically an autonomous option that individuals and firms could implement themselves, the social conventions around sticking to common working hours may create a barrier to implementing this measure. Therefore, government action may be required to incentivise this shift and coordinate actors to help actors move to a new equilibrium with adjusted working hours.

The right type of air conditioning unit might be optimal to complement other adaptation measures, to flexibly reduce peak temperatures, while other measures are used to reduce high base temperatures. A barrier to the latter may be a lack of awareness of the attributes of different technical options on the market, and how these can be used together. The appropriate policy in this case could be the development of minimum performance standards and usage guidelines, which should be tailored to market context.

The contextual factors described in Section 8.2 vary widely across the selection of case study countries.

Table 8 presents summary statistics for each of the countries based on the most recent available data (see notes to table). For example:

- India has by far the largest population and urban population, and is by far the most densely populated;
- All countries are expected to continue to urbanise, with most reaching over 50 per cent of population in urban areas by 2050;
- The CO₂ emissions intensity of electricity generation is far higher in India than in the other case study countries, and is more than three times as CO₂ intensive as Ghana.



	Ethiopia	Ghana	India	Jordan	Tanzania
Population (million)	100	28	1,309	9	54
Urban population (million %)	19 19%	15 54%	429 33%	8 84%	17 32%
Urbanisation rate 2007 – 2016 (annual average)	1.9%	1.5%	1.9%	1.1%	1.8%
Projected urban population share by 2050 (% total)	38%	70%	50%	89%	53%
Population density (ppl / sq km)	100	121	440	103	61
Access to electricity (urban)	92%	91%	98%	100%	41%
Access to electricity (rural)	12%	63%	70%	100%	4%
CO_2 emissions from elec and heat (grammes CO_2 /KWh)	1	243	813	656	389

Table 8. Summary statistics on context across the five case study countries

Source: Vivid Economics based on WB WDI data, and IEA CO2 emissions data, UN World Urbanisation Prospects

The following pages provide a series of case studies to discuss the application of a few of the shortlisted measures in different contexts. The purpose of the case studies is to describe how the difference in contextual factors affect the appropriateness of different adaptation options. We examine the following cases:

- Box 1 describes how shifting working hours can be effective, especially where productivity loss is driven by temperatures during the hottest part of the day, as small changes to move outside this window can have large impacts on productivity.
- Box 2 sets out how various contextual factors and cost structures means that air conditioning would need to be applied differently in the case study regions.
- Box 3 describes how structural economic transformation can have an important impact on mitigating labour productivity losses;
- Box 4 gives examples of how green roofs have been implemented in Northern America and Europe, and describes how they could be used at larger scale.

Where possible in each box, we present the potential impact of the intervention in terms of the

expected GVA loss that could be mitigated. This takes the expected loss in 2050 in the absence of any adaptation, estimated in Section 4 as the starting point, and then models the potential benefit (or dis-benefit) of implementing the adaptation measure. This illustrative approach is taken for both changing working hours and structural economic shifts, as these relate to changes in the underlying assumptions of the model developed in PART A. It is not done for the more technical adaptation boxes – that is AC and green roofs – as the precise amount of cooling degrees gained, and therefore the benefits and costs, will depend on the extent to which the measure is cost-effective to deploy. This will be heavily dependent on context, and the limits / effectiveness of the technical approaches – so providing even an indicative example would be arbitrary and risks being misleading. Instead we present some high-level policy conclusions in Section 10.







Box 1. Shifting Working Hours

How it works

Shifting working avoids heat-related productivity losses by shifting work away from the hottest parts of the day (while maintaining the total number of hours worked). The shift could include split shifts, an earlier shift, or seasonal shift patterns. The most appropriate policy will depend on the relative temperature differential at different times of the day or at different times of the year.

Potential impacts of changing working hours in different contexts

Changing working hour patterns will be most effective in countries where temperatures are high during 'normal' working hours, and lower at other times. We model two illustrative examples of changing working hours away from a baseline assumption of an 8 hour shift from 8 am to 1 pm and from 2 pm to 5 pm:

- 1. a 'split shift', with a morning shift from 8am to 1pm and then 5 pm to 8 pm;
- 2. an 'early start', with a first shift from 6 am to 11 am and a second shift from 12 pm to 3 pm.

Across the case study countries, we see that the 'split shift' reduces productivity losses in all contexts, while the 'early start' is always relatively less effective. The split shift reduces productivity losses by between 0.9 and 8 percentage points, equivalent to reductions in lost productivity between 40 per cent and 70 per cent across all five countries. By contrast, an early start approach only reduces productivity losses by only 0 to 3.6 percentage points, with a maximum percentage reduction of up to 20 per cent– and has almost no benefit in Ethiopia and no reduction in Tanzania.

Table 9.	Annualised productivity losses due to high temperatures in 2050										
Country	2050	2050 total annual productivity loss									
	Normal working hours	Split shift	Early start								
Ethiopia	6.0%	2.1%	5.9%								
Ghana	12.6%	6.3%	10.5%								
India	19.7%	11.7%	16.1%								
Jordan	1.4%	0.6%	1.3%								
Tanzania	4.1%	1.4%	4.1%								

Source: Vivid Economics

Time-shifting measures have different effects across different sectors. In all countries except Jordan, the first and second largest absolute reductions in labour productivity loss are in the agriculture and construction sectors, respectively. In Jordan, the construction sector sees the largest absolute benefit, followed by the 'other services' and manufacturing sectors. These results are the same regardless of time switching measure implemented. However, in relative terms, the two different measures benefit different groups to different degrees. In countries where the model indicates any loss of labour productivity in service sectors in 2050 (Ghana, India and Jordan), a split shift approach eliminates a greater proportion of the losses in the sectors



than for agricultural, manufacturing or industrial sectors. In contrast, while the reductions are small overall, the early start measure reduces relative productivity loss more for non-services sectors than in service sectors. In fact, it leads to no reductions in any of the three service sectors, with the exception of India, which sees an 11 per cent reduction in productivity loss in service sectors in moving from baseline hours to an early start approach.

These labour productivity loss reductions also reduce the impact on economic output. In some cases mitigating over half of the GVA losses modelled in PART A of this study.



Figure 17. Reductions in annual GVA losses in 2050 due to switching to a 'split shift' working pattern

Vivid Economics Source:

However, these results are based on a stylised application of a change in working hours, and do not take into account any costs of implementing the measure. The analysis above applies a uniform change to working hours across all sectors, all workers and all times of the year, and therefore represents an upperbound of the expected benefits from the measure. It also does not account for any socio-economic costs of applying the measure, such as disruption of work-life balance and international business arrangements. In reality, work-time shift may only be feasible for certain periods of the year, or in certain sectors - which would reduce the overall level of benefits from the measure, but also reduce any associated costs of implementation.

Application and precedent

There are various examples of working hours which vary by time of day or by season. While not all of these were implemented specifically to mitigate the impact of high temperatures on labour productivity, they do inform how a successful working hours policy could be implemented.

Traditional Spanish working hours include a long pause during the hottest part of the day to protect workers from the midday heat. A typical office worker begins at 9.00 am and takes a three-hour break pause during the hottest part of the day at 1.30 pm, finishing work at 8.00 pm. There have been some challenges in making this change. For example, the structure limits business interaction with other European





businesses that do not follow a similar pattern, and the 8.00 pm finish reduces the quality of parent-child interactions (Passport to Trade, 2014).

Japan and Norway promote seasonal shifts in working hours. Under the Japanese *Yukatsu* program, office workers begin around 8.00 am in July and August, an hour earlier than normal, and are encouraged to leave no later than 5.15 pm (The Japan Times, 2016). In Norway, public sector employees are encouraged to work eight hours in the dark winter to permit shorter seven-hour days during summer (Government of Norway, 2017.) The motivation for these seasonal shifts is mainly to increase leisure and family time in the long summer evenings (BBC News, 2015), but a similar programme could be effective in the context of heat impacts on labour productivity.

Developing countries have also considered or implemented shifts to working patterns. India's National Disaster Management Authority has warned against working practices that increase exposure to high temperatures. The Authority's 2016 guidelines for adapting to the threat of heatwaves, published after an estimated 2,400 Indians died during the heatwave of 2015, specifically advise workers to avoid direct sunlight, to schedule high intensity activities for cooler periods of the day, and to avoid working outside during peaks hours of 12.00 pm to 3.00 pm (Government of India, 2016). Jordan has also demonstrated the policy potential for shifting working hour patterns. In January 2000, Jordan government offices changed their weekend to Friday-Saturday, from its previous Thursday-Friday weekend, to increase alignment with international business practices (Associated Press International, 1999). This shows that government can induce large shifts in working behaviour.

However, this measure may not be feasible in all contexts. Adjustments of working hours may already be autonomously implemented by those workers that possess the ability to structure their working day, such as smallholder agriculture farmers, who are among the most exposed to labour productivity loss due to high temperatures. Additionally, the measure may not be feasible for workers that do not enjoy significant periods of leisure time, or who work for longer than a traditional eight hour working day.



Box 2. Air Conditioning

How it works

Air conditioning reduces indoor temperatures through cooling air and re-circulating it into the room. The extent and timing of cooling can be controlled flexibly by users, or optimised remotely. At a technical level, air conditioning could help indoor workers adapt to temperatures across all building types.

The type and cost of air conditioning unit will depend on the type of building and expected usage. Some units have relatively higher (/lower) fixed costs relative to variable costs. For some building types, AC may also be relatively less effective at a technical level. For example, in large open plan areas, building design and air flow may be better suited to reduce temperatures than individual air conditioning units. In practice, AC tends to be most beneficial for low and medium intensity indoor workers, as higher-intensity workers are more likely to work outdoors or in contexts that do not easily allow for air conditioning, such as in construction.

Some degree of AC is likely to be a *'low regrets'* option in countries with high and variable temperatures, where the ability to adapt to changes in temperature throughout the day is particularly valuable. AC can also be implemented in a relatively modular way, so can be phased in as appropriate over time.

Across all contexts, use of AC also increases emissions of Hydrofluorocarbons (HFCs) – which are a very potent greenhouse gas (at least 1,000 times that of CO₂). 170 countries signed the Kigali Amendment to the Montreal Protocol in October 2016, agreeing to slow the use of HFCs, which may impact on the feasibility of AC as an adaptation technique. Ratifying countries have committed to reduce HFC production and consumption by 80-85 per cent by the late 2040s. This phase-out could have substantial implication for the use of traditional air conditioning systems as an adaptation measure, though ongoing research efforts aim to identify HFC alternatives with less global warming impact.

Potential impacts of AC in different contexts

While at a technical level, AC can be used flexibly to reduce temperatures in indoor environments, there are limitations to large scale use arising from cost factors and indirect effects. For example, AC requires electricity, which may not be available in all contexts, it may be expensive, or it may become increasingly expensive as more AC is used.

Access to electricity is high in Jordan (100 per cent), so we might expect that the incremental costs of increasing air conditioning penetration or usage to be relatively low. No further infrastructure investment would be required, although it would be important to check that sufficient generating capacity is available and can be ramped up when needed. If air conditioning would place such a burden that it increases the risk (expected frequency) of power cuts, then the value of lost load (VOLL) would need to be taken into account.



In regions where access to electricity is low, such as in Ethiopia and Tanzania, the incremental cost of increasing AC usage or penetration may be high. In particular, where substantial new transmission, distribution or generating infrastructure would be required and where off-grid solutions are not costeffective.



Figure 18. Jordan's population has 100% access to electricity, while in Tanzania only 16% of the population has

Source: Vivid Economics analysis of World Bank World Development Indicators

Associated with the electricity generation required for AC, CO_2 equivalent emissions will also vary by region, depending on efficiency of generation and transmission, and the technology mix for generation. For example, India currently has CO₂ emissions more than three times higher than Ghana, while Jordan also has relatively high CO₂ emissions per kilowatt hour of electricity produced.





Source: Vivid Economics analysis of World Bank World Development Indicators

While AC reduces the internal temperature of buildings, it increases temperatures outside buildings, which can contribute to the urban heat island effect and to heat stress to people outside. This is likely





to have most effect in densely populated areas where the heat island effect is likely to be most pronounced. Increased outdoor temperatures may also have a feedback effect in reducing the cooling capacity of the installed AC units.

Air conditioning is relatively more effective than other options where there is high temperature

volatility. Figure 20 shows that while Ethiopia, Ghana and Tanzania are all projected to experience relatively constant, high temperatures across the year in 2050 within a range of around 4°C, India and Jordan will experience greater variation, with peaks between 14°C and 22°C above the lowest temperature. Air conditioning would offer significant flexibility for India and Jordan to cope with high temperatures during peak periods, while alternative measures that offer lower cost, year-round cooling may be more appropriate in Ethiopia, Ghana and Tanzania. There is also significant within-day variation in temperatures ranging from 5°C to over 15°C, and this variation also changes across the year. For example, in Jordan, the maximum within-day variation of 15.4°C occurs during the hottest period of the year in July and August. This substantial within-day variation in temperatures underscores the value of air conditioning as a flexible adaptation measure that can be easily adjusted to respond to temperature changes.





International programmes such as Sustainable Energy for All (SE4All) are likely to improve rates of access to modern and clean energy substantially in the coming decades. SE4All is crystallised in the UN's Sustainable Development Goals (SDG7), and targets universal access to modern energy, a doubling of the rate of energy efficiency, and doubling the share of renewable energy in the power mix by 2030. This type of global trend will make air conditioning relatively more attractive in the future as populations have better access to energy, which is potentially cheaper (efficiency) and has lower emissions.

Based on income levels only, AC penetration would be expected to increase steadily from relatively low levels today, by 2050. Drawing on studies (for example Isaac & van Vuuren, 2009) that estimate the





relationship between income and AC penetration we estimate that the expected stock of air conditioning would increase by over 400 per cent in India as shown in Table 10.

	Expected penetration of air conditioning based on cooling degree days and income levels									
	Household penetration in	Household penetration in	Percentage change							
	2015	2050								
Ethiopia	1.9%	3.4%	+ 76%							
Ghana	2.9%	7.0%	+ 139%							
India	3.0%	15.9%	+ 429%							
Jordan	3.8%	8.0%	+ 110%							
Tanzania	2.1%	3.3%	+ 56%							

Source: Vivid Economics

Application and precedent

To the extent that the most important gains operate directly upon the individual or firm, end users are well incentivised to use AC where it is cost effective to do so. AC is used at least to some extent in all of the case study countries, and we would expect a relatively competitive market of suppliers to meet firm and individual demand.

However, absent policy intervention, the extent of AC penetration and usage may not be optimal; in particular AC may be over-used. This is because most of the indirect impacts – that is those impacts that affect people other than the direct users / suppliers of AC – have a negative broader impact. For example, individual users may not take into account the implications for forward-looking energy systems costs associated with increased AC use or penetration, as the price signal they receive is today's unit electricity price. Furthermore, the impact of increased outdoor temperatures in urban areas would not be factored in by individual or firm decisions.

In regions where there is limited access to grid electricity, and/or where the cost of using electricity is relatively high, there may be a constraint on businesses being able to afford AC, even where it is optimal to do so. This may be especially true in rural areas and/or for small enterprises, if there are constraints in access to loan facilities.



Box 3. Structural economic shifts

How it works

Structural economic shifts can reduce heat-related productivity losses by reducing the exposure of workers (and associated GVA) to high temperatures. Shifting economic activity from sectors most exposed to high temperatures – either because they are outdoor or high-intensity – to sectors with low exposure would reduce the impact of heat on worker productivity. For example, shifting employment from agriculture to manufacturing, industry and services reduces both the number of workers exposed to high temperatures, and the impact of those temperatures on subsequent economic output.

Economic shifts are rarely driven by climate, but adaptation may involve accelerating planned economic transition, or reorienting plans to account for labour productivity impacts. Planned or autonomous economic shifts may increase exposure to heat stress, for example if there will be greater activity in the construction sector in the future. Similarly, shifts that involve shifting workers to more productive sectors could reduce the direct impact on labour hours lost through reduced productivity, but increase the impact on GVA loss.

Potential impacts of economic shifts in different contexts

Structural economic shifts will have the highest impact in countries with a high proportion of workers in exposed sectors, particularly agriculture. They will be less effective in highly diversified economies or where GVA primarily comes from service sectors.

We first model an illustrative example where all countries transition 50 per cent of agricultural labour to other sectors. This includes an accompanying reallocation of 50 per cent of the capital stock from the agriculture sector to other sectors (in each case proportional to the sector's initial share of non-agricultural labour and capital respectively). The modelled impact of this stylised shift is to:

- reduce labour productivity losses by half in the agriculture sector,
- increase labour productivity losses in all other exposed sectors of the economy;
- increase economic output in all countries compared to a no-change baseline, largely because the stylised shift in workers moves them from a low productivity per person sector to a higher productivity sector;
- decrease proportional temperature-related GVA losses, especially in large countries that have a large initial proportion of workers in the agriculture sector, as shown in Figure 21.

Figure 22 presents two further stylised examples, by showing what the losses would look like if by 2050 each case study country had the same sector composition as Ethiopia or Jordan. These represent the two extremes of the country case study labour forces, as Ethiopia currently has the highest share of employment in agriculture, while Jordan has the lowest. Shares of employment and capital within the broad industry and service sectors are allocated according to original shares within the broad sectors in each country. To take two clear, and intuitive, results from this stylised example:

were Jordan to have the sector composition of Ethiopia, it would suffer vastly higher GVA losses by 2050, as shown by the large red hatched bar in the left panel of Figure 22;

: vivideconomics





 were Ghana to move towards the service oriented sector composition that Jordan currently has, it would suffer a far smaller GVA loss by 2050, compared to its largely agricultural economy today.

This stylised transition does not account for any changes in sectoral productivity nor to capital-labour substitutability. It does not include any changes in sectoral overall productivity, which might change due to improvements in technology or per-worker productivity, such as increased mechanisation in the agriculture sector. Furthermore, it does not include changes in the intra-sector substitutability between capital labour, which may adjust over time if, for example, the substitutability of workers relative to capital decreases due to increasing productivity of capital. These factors would complicate the assessment of the value of economic structural shifts as a means of adapting to climate change impacts on labour productivity.





Source: Vivid Economics analysis of World Bank World Development Indicators





Source: Vivid Economics analysis of World Bank World Development Indicators

Application and precedent

No countries have initiated economic shifts as an explicit means of adapting to climate change, but economic transformation often figures in national growth or development plans. All of the case study





countries have implemented structural shifts over the past 25 years, with a general decline in the share of agriculture since the early 1990s and significant increases in industrial and service sectors (World Bank (2017). Examples from national growth plans include:

- Ethiopia's second Growth and Transformation Plan aims to decrease the share of agriculture in GDP from 38.5 per cent in 2016 to 33.5 per cent by 2020 while also increasing the productivity of the agriculture sector (Federal Democratic Republic of Ethiopia, 2016);
- Ghana's second Ghana Shared Growth and Development Agenda (GSGDA) from 2014 to 2017 included goals to improve the productivity of the agriculture sector, while at the same time envisioning a decline in the agricultural share of GDP to 17 per cent by 2017 (National Development Planning Commission, 2014);
- Tanzania's Five Year Development Plan aims to moderately increase the agriculture sector's share of GDP from around 30 per cent in 2015 to 32 per cent by 2025, while decreasing agriculture's share of total employment from around 67 per cent in 2014 to just over 40 per cent by 2025 (Ministry of Finance and Planning, 2016);
- India's latest, draft 2017-2020 Three Year Action Agenda does not include a specific transformation goal for agriculture or other sectors, but aims to enhance agricultural productivity (NITI Aayog, 2017);
- In contrast to the other case study countries, Jordan's 2018-2022 Economic Growth Plan aims to increase the share of agriculture's share in the economy by 2022, primarily through increased productivity rather than through increasing the proportion of the labour force employed in agriculture (Economic Policy Council, 2017).

Country		1990			2015	
	Agriculture	Industry	Services	Agriculture	Industry	Services
Ethiopia	52.0%	9.8%	38.2%	39.2%	17.7%	43.0%
Ghana	45.1%	16.9%	38.1%	21.0%	27.6%	51.4%
India	30.1%	31.6%	38.3%	17.5%	29.6%	52.9%
Jordan	7.7%	26.2%	66.0%	4.2%	29.6%	66.2%
Tanzania	46.0%	17.7%	36.4%	31.1%	26.1%	42.9%

Table 11. Structural economic shifts from 1990 to 2015 (sectoral value added as a percentage of GDP)

Source: Vivid Economics

Structural shifts implemented for economic reasons are likely to have significant climate change adaptation co-benefits for labour productivity impacts. Countries are unlikely to implement structural economic shifts for the specific purpose of reducing heat impacts on labour productivity, but the benefits of such transitions for adapting to climate change increase the benefits of transitions. These shifts and their potential to create greater exposure in sectors where workers have a greater per-person economic output also highlight the importance of managing transitions to avoid over-concentration of workers in high-exposure sectors. They also increase the potential benefit from other measures to adapt to the impacts of high temperatures on labour productivity, such as shifting working hours, air conditioning, green roofs or other measures shortlisted in this analysis.



Box 4. Green roofs

How it works

Green roofs reduce the local temperature by absorbing less solar energy. They have a higher albedo (reflectivity) than traditional 'grey' roofs, meaning they absorb less solar energy from the sun's rays (Foster, Lowe, & Winkelman, 2011), with two effects: (i) less heat is transferred into the building, (ii) the air around a green roof remains cooler, reducing the Urban Heat Island effect (Claus & Rousseau, 2010).

Potential impacts of green spaces in different contexts

Green roofs are most effective in high-density urban settings. The internal cooling effect works the same for both urban and rural environments. However, most of the benefits derived from green roofs are public, not private, and so are realised for the city as a whole. The Urban Heat Island effect is strongest in high-density city centres: as density increases, more solar radiation is absorbed and ventilation decreases. In addition, green roofs provide positive public co-benefits of reducing pollution, dampening noise, increasing biodiversity, mitigating flash flooding, and improving mental health. These problems are all more severe in more dense cities. This means that the benefits of green roofs are most pronounced in high-density urban environments.

India has by far the highest urban population, and overall population density cities of the five case study countries. Jordan, Ethiopia, and Tanzania each have just one city with a population above one million, while Ghana has just two. India, however, counts 46 cities with a population above one million. Figure 23 shows all five high-population non-Indian cities, as well as the eight most populous Indian cities. The figure shows that India has the most dense and most populous cities.

India's slums complicate the installation of green roofs. Out of all five case study countries, India has the most dense cities and so green roofs are most applicable in India. However, India's big cities are renowned for their slums. For example, the Dharavi slum in Mumbai houses one million people with a population density of 335,000/km². Green roofs are clearly not a realistic expectation for basic or temporary accommodation.







Figure 23. India has the largest and most densely populated cities across the case study countries



Application and precedent

Green roofs are not uncommon in concentrated populations in Western Europe and North America. In 2001, Chicago installed a 20,300 square-foot green roof on its City Hall as part of the Mayor's Urban Heat Island Initiative. The roof contains 20,000 plants, shrubs, grasses, vines, and trees (Foster et al., 2011). In Toronto, the not-for-profit organisation '*Green Roofs for Healthy Cities*' offers education on green roofs (Banting, Doshi, Li, & Missious, 2005). In Flanders, Belgium, there were almost no green roofs constructed in the early nineties. By 1995 there were 20 green roofs in place, growing to 509 in 2002; by 2010 in Flanders, green roofs were installed on sixty times more roof area than in 2003 (Claus & Rousseau, 2010). A green roof research station was installed in 2006 in New York City (Rosenzweig, Gaffin, & Parshall, 2006).

Public subsidies are required to coordinate city-wide green roofing. The majority of green roof benefits accrue to the city as a whole and not directly to the building owner. The benefits increase as the coverage increases. Subsidies are therefore required to incentivise private installation of green roofs; for example, in Flanders, Belgium, the government ran a subsidy of \$36/m² of green roof (Claus & Rousseau, 2010). The City of Toronto valued their subsidy three times higher at \$108/m², with a maximum total spend at \$20,000 per building (Ligeti, 2007).

Green roofs are more effective at reducing indoor temperatures if the roof is uninsulated. The cooling benefits are smaller for insulated roofs. The external cooling effect lasts longest during hot, still and sunny conditions, which correspond to when the urban heat island effect is most pronounced. Based on modelling of a typical London office building, green roofs unsurprisingly become less effective when they are not irrigated during warm periods (Virk et al., 2015).



10 Recommendations for Policy Makers and Practitioners

The optimal mix of adaptation options will be heavily dependent on context and would need to be subject to a context-specific assessment of technical options and their relative costs and benefits. What is appropriate for Amman (Jordan), will be very different from what is best for Mumbai (India), and different again for rural Tigray in Ethiopia for example. Given the paucity of evidence on context specific costs and benefits, this study stops short of making an absolute ranking of adaptation measures.

Nonetheless, the analysis presented in PART A and PART B leads to some high level conclusions about which adaptation measures are most likely to be effective in different circumstances. These are presented in the following paragraphs by identifying: (i) where the largest identified productivity losses are concentrated, (ii) which adaptation measures appear to have large potential for mitigating productivity losses, at low expected cost, (iii) which measures are likely to be low-regrets – that is cost-effective in all future scenarios – across most contexts, (iv) which options are likely to be part of the portfolio, but would need to be carefully considered how much they should be used in combination with other measures.

The stylised model presented in PART A shows that the largest impact in almost all countries is on outdoor workers, in particular agriculture and construction. This is especially true for lost effective working hours, but remains true even when considering GVA losses even though outdoor work is often less productive on a per-worker basis so these outdoor sectors tend to have a lower impact on GVA losses than on working hour losses.

The largest levers, as shown in the technical boxes in PART B, identify potentially substantial opportunities from shifting working hours, and economic transformation. In India, where the amount of work hours lost due to heat is concentrated in a couple of months of the year, with other months experiencing no losses, policies to investigate the extent to which working hours could be moved to the cooler winter months, or to cooler parts of the day in summer months, appears to be a promising impact mechanism. Similarly, economic transformations that result in fewer workers in sectors of the economy that are highly exposed to high temperature impacts, especially those that involve high intensity, outdoor labour, have the potential to substantially reduce the impact of climate change on lost labour productivity. These types of economy-wide policy shifts are likely to have the biggest potential adaptation impact, but would require careful policy design and may have significant social implications.

Passive cooling mechanisms, while possibly not as high impact as some technical options, are likely to be 'low regrets' in almost all indoor contexts. Behavioural change, such as encouraging regular drinks breaks, cool showers on-site, or spatial zoning to allow workers to avoid heat where possible, are likely to be low cost and can work in complement to all other adaptation options. While not appropriate as the sole solution, these types of 'passive' measures should be identified in relevant contexts and implemented alongside other adaptation measures being considered.





The benefits and costs of capital-intensive technical options such as air conditioning and green roofs will be heavily context-specific and should be considered through a more detailed, thorough technical assessment. This should include identifying the extent of barriers to the autonomous adoption of the optimal amount of each measure.

While a general ranking of adaptation solutions is not possible, with value-for-money estimates varying substantially within countries, some high-level implications for each of the case study countries can be drawn:

- In Ethiopia, the impacts are heavily concentrated in the agriculture sector. An economic transformation programme orienting the economy away from high-intensity, outdoor work as is already being implemented under the current national development plan is most likely to have a bigger impact on productivity losses than specific adaptation measures. However, structural change needs to be accompanied by a program to develop urban areas and newly developed service sectors so as to minimise the impact of heat on indoor workers as temperatures rise. For example, through passive cooling and a mix of technical options such as AC or green roofs, although this is a much more secondary concern. To the extent that economic transformation may not be realistic (or even necessarily desirable, for other reasons), avoiding the hottest parts of the day would have potentially large adaptation potential to the extent this is not already optimal in practice.²⁰
- In Ghana, where productivity losses are felt throughout the year, measures that reduce the impact of high base temperatures may be most effective. After working hours, economic transformation and passive cooling measures, this may lean toward technical options such as shading, rather than AC which, while a part of the solution space, may be relatively less cost effective than in other settings, especially due to the large number of outdoor workers in agriculture and construction.
- In India, impacts are relatively concentrated in outdoor work such as agriculture, but are particularly concentrated in specific months of the year. Any policies that could shift working hours away from these hottest months of the year would have high adaptation potential. Where this is not possible, and given the difficulty in proposing for example green roofs in some of the more densely populated urban areas, appropriate use of AC to respond flexibly to high temperatures is likely to be needed but this is likely to be highly costly and have negative climate change impacts without efforts to reduce both the energy intensity of AC and the carbon intensity of electricity consumption. Passive cooling mechanisms should be implemented before relatively more expensive technical options, such as cool showers, regular cool drinks breaks and so on.
- In Jordan, which is highly urbanised with a diverse economy and universal access to electricity, technical
 options may be relatively more cost-effective than in other settings. For example, green roofs could be





²⁰ Modelling results are indicative only and based on default working hours of 8am to 1pm and 2pm to 5pm. In practice there will be (potentially large) variation from this across countries and sectors.

explored in major urban settlements to reduce the heat island effect, and appropriate use of AC is likely to remain a key part of the solution space, although shading may be equally or more cost effective. Nonetheless, the majority of impacts are on the construction sector, where policies such as working in the coolest parts of the day and year have most potential to be effective, and where many technical measures may not be effective.

 In Tanzania, the temperature profile and economic structures look broadly comparable to Ethiopia; a similar adaptation response would be appropriate.

The value for money of different adaptation options also depends on the exact development objectives. The focus of many DFID programmes on poverty and/or specific sector objectives may mean some adaptation solutions are preferable to others for reasons not directly related to the aggregate impact on labour productivity. For example:

- For programmes that focus on poverty reduction, a number of measures might be ruled out due to their high costs (such as air conditioning or green roofs) or because they are unlikely to deliver benefits for key target groups. For example, relatively high-cost technical measures will have limited benefits to poor, rural agricultural communities. Lower cost options better suited to the context of lower income households and workers may be preferable, such as adapting working hours for subsistence farmers, increased building albedo through white paint, and design of cities and public spaces to minimise heat impacts for the urban poor.
- An infrastructure development programme is likely to focus on measures falling within the technical response and regulatory and infrastructural response groupings of actions, before applying the same national or sub-national contextual factors. Measures that are highly appropriate for urban settings may also offer particularly high value-for-money within urban development programmes. Conversely, measures that need to be delivered through high-level policies, such as promoting an economic structural shift or encouraging behavioural change, may be less appropriate for these programmes.
- Similarly, an agricultural development programme is likely to focus on options that are particularly strong
 in outdoor and rural settings. While these include some technical measures, such as mechanisation and
 outdoor shade, regulatory or behavioural measures such as promoting structural economic shifts,
 adjusting working hours or implementing individual-level heat reducing activities are likely to offer the
 best value for money adaptation to high temperature impacts on labour productivity.





11 Concluding Remarks

This report makes four contributions to the literature:

- focussed synthesis of the literature on the impacts of increased temperature on labour productivity;
- simple but usable modelling framework to consider the scale of impact which can be easily extended to other contexts;
- mapping of the adaptation solution space into different types, and primary drivers, of adaptation;
- decision-making framework for adaptation faced with uncertainty and where VfM will be heavily dependent on contextual factors.

The results presented in PART A of this study show that the impact of heat on labour productivity is substantial, in absolute terms and relative to other climate change impacts. While the quantitative modelling shows potentially declining GVA impacts over time in relative terms (as a percentage of total GVA), which is a result of an increase in the capital : labour ratio, the absolute impact on GVA increases over time. Nonetheless, the case study countries see substantial GVA losses of up to 3 per cent in some scenarios by 2050 (and of close to 5 per cent in the baseline year 2015); and this is likely to be a conservative lower bound given the assumptions made. This is consistent with the broader literature, which identifies labour productivity impacts as an important climate change mechanism, and identifies heat as one of the major drivers of productivity impacts.

PART B demonstrates that a mix of technical, regulatory and behavioural measures would be appropriate to adapt to increasing temperatures, depending significantly on context. Technical and behavioural measures will largely be driven by individuals or firms, while governments would lead regulatory and infrastructural measures, and create frameworks and incentives to facilitate optimal adaptation by firms and individuals. The range of suitable, value for money responses to heat impacts will depend on contextual factors, such as flexibility of response to future climate change scenarios, and rates of urbanisation, access to clean and affordable electricity and so on. The technical case study boxes demonstrate that the applicability of all the measures can vary significantly across countries, depending on the structure of the economy, climatic conditions and social characteristics such as rates of urbanisation and population density.

There are a number of areas outside of the scope or timeline for this study which would be valuable areas for further research. Some of these are presented below.

The model used to estimate the impact of heat on labour productivity is a simplified country-level representation, built on a number of assumptions. These assumptions could have important impacts on the results, either on the distribution of impacts or in general implying the impacts estimated in this study are relatively conservative, and could be explored further:

1. <u>Each sector of the economy is treated separately with no explicit inter-relationship between sectors.</u> It does not allow for 'automatic' rebalancing of economic activity (capital and labour) between sectors in response to temperature increases. Incorporating automatic rebalancing through a general equilibrium



approach would be a useful extension, optimising across multiple objectives, - including labour productivity impacts – and investigating dynamic effects such as short term frictions.

- 2. <u>Each country is treated as a single spatial unit masking within country variations in temperatures and economic impacts</u>. In reality, temperatures and the composition of the economy will vary widely within countries, with important distributional effects and implications for adaptation or regional development policy. This variation could be particularly important in large and geographically diverse countries such as India. This could impact results in one of two ways. First, using national averages masks variation within the country. Variation (around the average) in itself would increase the impacts modelled, as it would push temperatures above the 26 WBGT more frequently (while also pushing temperatures more often into a cooler range, with relatively less impact on results where temperatures are not already always above 26 WBGT). Second, the national economy and national temperature estimates will not be representative if workers within a country are concentrated in relatively hotter or relatively cooler regions, which would increase or decrease the modelled impacts respectively.
- 3. <u>No explicit treatment of the impact of workers in urban versus rural areas.</u> Sectors are categorised as 'indoor' or 'outdoor', but not mapped explicitly to urban or rural areas. Given that economic activity is often concentrated in cities, and cities may suffer from an additional urban heat island effect, the urban-rural divide could be important from a distributional perspective. Outdoor rural workers experience the largest expected reductions in effective work hours, while densely populated cities may be drivers of economic output where labour productivity and GVA reductions may be exacerbated by additional temperatures due the urban heat island effect.
- 4. <u>Daily temperature profiles on a simplified set of representative monthly profiles.</u> We use a representative day for each month of the year, which masks potentially important variation of temperature within a given month. This is important as if there is a wider distribution of temperatures within a month, it may mean that the temperature extremes under which productivity losses are incurred occur more frequently than the monthly average representative day would suggest. As discussed in bullet "2" above, increasing volatility in temperatures would be more likely to increase the impacts estimated than reduce them.
- 5. <u>Potential impacts of temperature increases on human capital accumulation and economic growth are</u> <u>not examined.</u> This analysis does not consider the impact of higher temperatures on the growth rates of GDP, through a longer-term impact on the accumulation of 'human capital'. Incorporating a growth impact, alongside the levels impact assessed in this report, would increase the estimate of potential losses.
- 6. <u>Cumulative or lagged impacts of persistently high temperatures could increase the impacts.</u> This study only considers contemporaneous, that is in-hour, labour responses to higher temperatures. It does not consider the impact of persistently high temperatures, or high temperatures across non-working hours (for example overnight) on human welfare and productivity. This would also tend to increase the impacts estimated in this study and may have implications for the optimal adaptation solutions where temperatures should be reduced across all hours of the day and night (at work and home environments), not just for active working hours.


To determine the appropriate portfolio of adaptation solutions in specific contexts – and how public policy can help achieve these – a few further policy research areas are highlighted:

- The degree to which adaptation options will be taken up autonomously, through market mechanisms. This report has provided some initial analysis on likely future trends, and case studies for a subset of the adaptation solutions that describe how adaptation uptake is likely to evolve in the absence of policy intervention. Further research could focus on the barriers to uptake of adaptation solutions, to identify where policy is most needed and will have the biggest impact. For example, the constraints to optimal use of air conditioning may be very different to optimising working patterns For example, financing constraints, lack of information, or factoring in 'externalities' such as greenhouse gas emissions for the former, and the need for a centralised policy initiative to implement behavioural response or green roofs where the benefits rely on all or most people adapting.
- <u>Context specific analysis of costs and benefits.</u> There may be substantial variation in the cost of measures, depending on the context. For example, changing behaviour and social norms in dispersed rural areas may be easier (or harder) than in a large city with embedded business practices. Similarly, the costs and benefits of technical options will depend on contextual factors. For example, the cost of widespread use of air conditioning may be very expensive in dispersed rural areas, for relatively little benefit where the impacts are largely felt by outdoor workers.
- Local variations on adaptation options. The analysis presented here is at a global level, with a focus on high-level policy design. How adaptation options are implemented in practice at a local level is an important consideration for policy. For example, indigenous architecture may be appropriate as part of the adaptation response, and the implementation of adaptation measures should draw on local knowledge and best practice, while also drawing on international best practice.



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Appendix A - Selection of Case Studies

We focus on five DFID high-priority countries,²¹ based on an assessment against selection criteria. The objective of these criteria is to identify country case studies which provide an interesting range of potential impacts and adaptation options, and for which we can identify reliable data with a reasonable degree of confidence. The five countries selected are:

- Ethiopia
- Ghana
- India
- Jordan
- Tanzania

Country selection criteria

The analytical approach presented in the main body of the report applies a flexible modelling tool to a sub-set of DFID priority countries. This approach provides directly applicable evidence for the five countries selected, and can be used as a reference point for other countries with similar characteristics or experiencing similar challenges. The model could also be updated to feed in data from other countries at a later date.

Four criteria were applied to identify an appropriate selection of countries case studies:

- <u>Potential temperature increases:</u> Some countries will be more (less) affected by projected temperature increases, which will affect the expected impact on labour force productivity.
- <u>Current sector economy composition</u>: Temperature increases will affect different sectors of the economy to different degrees. Sectors requiring intensive human labour and outdoor working (e.g. agriculture and construction) may experience stronger productivity impacts than less intense and indoor work.
- <u>Population composition and trends</u>: Growing population and trends in urbanisation may also determine a country's vulnerability to heat-related labour productivity impacts (e.g. urban heat island effects). These trends will also affect the appropriateness of different adaptation options
- <u>Availability of critical data:</u> An assessment of the availability of key data is important for ensuring that there is sufficient existing baseline data to support the application of the modelling framework in the selected countries. Key variables of interest include sectoral gross value added (GVA), sectoral employment data, future temperature profiles under climate change scenarios.



²¹The countries where DFID operates, as listed at <u>https://www.gov.uk/government/organisations/department-for-international-development/about#where-we-work</u>

Table 12. DFID's 32 priority countries are drawn from a range of regions

Africa	Middle East and central Asia	South and South East Asia
Democratic Republic of Congo	Afghanistan	Bangladesh
Ethiopia	Iraq	Burma
Ghana	Jordan	India
Kenya	Kyrgyzstan	Nepal
Liberia	Lebanon	Pakistan
Malawi	Occupied Palestinian Territories	
Mozambique	Syria	
Nigeria	Tajikistan	
Rwanda	Yemen	
Sierra Leone		
Somalia		
South Africa		
Sudan		
South Sudan		
Tanzania		
Uganda		
Zambia		
Zimbabwe		

Source: Vivid Economics, based on <u>https://www.gov.uk/government/organisations/department-for-international-</u> <u>development/about#where-we-work</u>

The five countries selected for case study analysis – Ethiopia, Ghana, India, Jordan and Tanzania – provide a range of interesting contexts in which to consider the impacts of temperature increases on labour productivity. These five countries are expected to experience a range of different temperature increases by 2100. The different countries also currently have differently-structured economies, with differing levels of agricultural, industrial and services contributions to GVA, and differing levels of employment levels and intensities within these sectors, which will have interesting implications for the analysis of the impact of temperature increases on sectoral and overall labour productivity. They also have varying levels of urbanisation, and have experienced different trends in urbanisation since 2005.



Table 13.The five countries selected for case study analysis are drawn from different regions and vary across
economic, social and climatic criteria

Country	Future temperature	Sector e (2015, % of	conomic com GVA % of em	Population	composition	
	Potential increase to 2100 (°C)	Agriculture	Industry	Services	Urban population (2015, %)	Urbanisation (2005 to 2015, CAGR)
Ethiopia	4.2	41 73	16 7	43 20	19	119
Ghana	3.7	21 45	28 14	51 41	54	1
India	4.2	17 50	30 22	53 29	33	91
Jordan	4.9	4 2	30 19	66 80	84	-1
Tanzania	4.0	31 67	26 6	43 27	32	-4

Source: Vivid Economics, based on Burke et al. (2015a) for potential temperature increases to 2100, based on IPCC CMIP5 modelling and the RCP8.5 scenario, and World Bank Group (2016) for all other indicators.



Appendix B– Defining the WBGT

In order to measure the impact of heat on labour productivity, we must first define what we mean by *'heat'*. The way in which *'heat'* affects human health and productivity is broader than just the *temperature*. Other factors, such as *humidity* and incidence of *solar radiation*. For example, a day reaching 30 degrees Celsius in London feels very different from a day reaching 29 degrees Celsius in Mumbai, or in Dar Es Salaam. Or, to give a different example, 30 degrees in direct sunlight is a different experience to 30 degrees in the shade.

A common measure of heat for the purposes of modelling productivity impacts is the Wet Bulb Globe Temperature (WBGT) index of heat stress. The WBGT index which incorporates air temperature, solar radiation, and humidity. There are a number of methods available to calculate WBGT using data available from weather stations and climate models(Lemke & Kjellstrom, 2012).

Throughout this report we apply the modified Australian Bureau of Meteorology (ABM) method. This method has been selected as the core ABM method is straightforward to implement in practice in a modelling exercise, and has been used in other similar studies for this reason (Lemke & Kjellstrom, 2012). The ABM method is less sophisticated than some other methods for estimating WBGT as it does not include direct measures of solar radiation or wind speed, as included in other models such as the 'Bernard et al.' and 'Liljegren et al.' methods, which are recommended as best practice for estimating indoor and outdoor WBGT, respectively (Lemke & Kjellstrom, 2012). However, these methods are not feasible to apply in a straightforward model tool as developed for this analysis. In applying the more straightforward ABM approach, we apply the modified version as re-calculated by Lemke & Kjellstrom (2012) that includes re-estimated key parameters to provide a better match between modelled and observed WBGT values. However, the model also includes the original Australian Bureau of Meteorology method to enable users to conduct sensitivity analysis.

where: $\rho = \left(\frac{RH}{100}\right) * 6.105 \exp(17.27 * Ta/(237.7 + Ta))$





Appendix C – Temperature Impacts on Productivity

Table 14. Many studies have established a link between higher temperatures and reduced labour productivity

Study	Context	Findings
Adhvaryu, Kala, & Nyshadham (2016)	Effect of indoor temperature on manufacturing productivity, India	Manufacturing worker efficiency declines on hotter days due to reductions in task productivity rather than increased absenteeism
Cachon, Gallino, & Olivares (2012)	Impact of heat stress on automobile manufacturing plant output, United States of America	Hot days are associated with lower output: on average, a week with six or more days of heat exceeding 90°F (32°C) reduces production in that week by 8%
Graff Zivin & Neidell (2014)	Effects of temperature on workers' time use (to work, leisure) in the United States of America, for overall workers and comparing 'high risk' sectors (agriculture, construction, manufacturing, transportation, utilities) and 'low risk' sectors (all others)	At temperatures above 85°F (29°C), workers in high risk industries reduce daily output by as much as one hour, reallocate time to indoor (air conditioned) leisure No impact for low-risk sectors
(Heal & Park, 2013)	Examine the general labour productivity relationship with temperature using country-level data, 1950-2005	Hotter-than-average years lead to lower output in hot countries, but lead to higher output in colder countries (as hot years are associated with increased productivity) – the relationship is around 3% or 4% change in labour productivity per °C variation
Hsiang (2010)	Impact of temperatures and tropical cyclones on agricultural and non-agricultural production in 28 Caribbean countries, 1970-2006	On average, a 1°C temperature increase is associated with a 2.4% reduction in non- agricultural production and a 0.1% reduction in agricultural production (after controlling for the influence of tropical storms)
Kopp et al. (2014)	Review of previous literature on labour productivity effects of heat stress	Higher temperatures lead individuals to spend more time indoors, take more frequent breaks, reduce cognitive capacity and endurance
Nag & Nag (1992)	Experimental evidence of effect of heat stress on women doing manipulative work, India	Increased atmospheric temperatures are associated with increased oxygen uptake, core and skin temperatures and feelings of heat discomfort
Niemelä, Hannula, Rautio, Reijula, & Railio (2002)	Effect of heat stress on daily productivity of Indian call centre workers	Above 72°F (22°C) each additional °C is associated with a 1.8% reduction in labour productivity
Park (2016)	Impacts of temperature shocks on country-level output (measured through payroll) across the United States of America, 1986-2012	Hot days have adverse effects on production: for the average county, an additional day above 90°F (32°C) results in a -0.048% decline in payroll per capita that year
Sahu, Sett, & Kjellstrom (2013)	Impact of heat exposure on cardiovascular stress and work productivity in rice harvesters in India	Hourly productivity decreases significantly once temperature exceeds a threshold, by 5% per degree over 26°C WBGT
Seppänen, Fisk, & Lei (2006)	Review of previous literature on task performance in office environments	Task productivity improves up to a temperature threshold around 20°C to 25°C, then declines significantly Average productivity loss around 2% per °C





Sudarshan,		Indian manufacturing worker efficiency declines
Somanathan, Imp Somanathan, & pro Tewari (2015)	npact of temperature on manufacturing oductivity and labour supply in India	substantially on hot days, by c. 2.8% per °C, an effect that is driven primarily by on-the-job task productivity decline as opposed to missed days of work (absenteeism)
Wyndham (1969) Exp pro	xperimental evidence on the effect of air mperature and wind speed on labour oductivity, South Africa	Above a 'wet bulb temperature' of 27°C, there is an exponential decline in performance for manual labour tasks

Source: Vivid Economics, based on Hallegatte et al. (2016), Kjellstrom et al. (2016), Heal & Park (2016) and original research



Appendix D–Heat : Productivity Relationships

Figure 24. The evidence suggests a common pattern of sharp labour productivity loss above a threshold

Panel 1: Percentage productivity loss with increase mean hourly WBGT, from different studies and at different intensities



Panel 2: Percentage <u>remaining productivity</u> at differing mean hourly WBGT levels estimates from the High Occupational Temperature Health and Productivity Suppression (Hothaps), for different work intensity levels







Source: Vivid Economics, based on Kjellstrom et al. (2015), Kjellstrom et al. (2014), Kjellstrom, Kovats, Lloyd, Holt, & Tol (2009)



Appendix E – Shortlisting Adaptation Options

Table 15. Identifying a shortlist 21 options for detailed inclusion in the modelling framework

#	Adaptation response	Туре	Actor	Feasibility	Impact potential L / M / H	Shortlisted	How this response operates
1	Air conditioning	Technical	firm	н	Н	~	Increased use of installed air conditioning units decreases inside temperatures in work spaces that already have air conditioning installed Increased prevalence of air conditioning units to expand the number of work places that are able to reduce internal temperatures
2	Increased thermal mass (heat absorption)	Technical	firm	м	М		Increased ability of buildings to absorb and store heat energy, so that internal building temperatures increase more slowly over time, reducing internal temperatures
3	Increased ventilation	Technical	firm	М	L	~	Increased ventilation (natural or mechanical) can reduce heat through increasing flow of cool air through buildings.
4	External building shade	Technical	firm	н	М	1	Increased shade reduces direct solar radiation entering buildings, reducing internal temperatures.
5	Internal building shade	Technical	firm	н	М	~	Increased internal shade (for example, curtains or window film) shade reduces direct solar radiation inside buildings, reducing internal temperatures.
6	Reduced internal gains: reduced lighting	Technical	firm	н	L		Reduced lighting eliminates internal source of heat in buildings.
7	Reduced internal gains: reduced use of heat-outputting devices (e.g. electronics, ovens, furnaces)	Technical	firm	L	М	~	Reduced use of heat-outputting devices eliminates internal source of heat in buildings, including reduced use of heat-outputting devices (e.g. electronics, ovens, furnaces)
8	Increased roof (/wall) albedo	Technical	firm	н	М	1	Increased roof albedo leads to increased reflection of solar radiation for buildings, reducing solar heat gains
9	Green roofs	Technical	firm	н	М	~	Green roofs are roofs that are partially or completely covered with vegetation. Green roofs can improve the thermal performance of roofs, reduce cooling loads on buildings, and reduce average temperatures in the vicinity of the roof by reducing re-emission of solar radiation as heat.
10	Mechanisation (reduce work effort level)	Technical	firm / ind	Н	Н	~	Increased use of mechanisation in labour-intensive activities to reduce level of effort required by workers, thereby reducing heat stress.



#	Adaptation response	Туре	Actor	Feasibility L / M / H	Impact potential L / M / H	Shortlisted	How this response operates
11	Outdoor shade	Technical	firm / ind	М	Н	√	External shade reduces direct solar radiation felt by outdoor workers, including both artificial structures and natural shade (trees, plants).
12	Improved technical standards for buildings	Regulatory & infrastructural	govt	н	L		Building-level design and regulatory standards that lead to reduced internal temperatures, through overall building design including, for example, green roofs.
13	Improved technical standards for climate-appropriate technologies (e.g. ventilation, insulation, building materials)	Regulatory & infrastructural	govt	н	М		Technical standards for specific technologies or their use to reduce internal temperatures in buildings (for example, natural ventilation, materials for increased thermal mass, use of insulation to avoid increased internal heat gains).
14	Climate smart design (zoning, municipal planning, etc)	Regulatory & infrastructural	govt	М	н	4	City-, zone-, region- or country-level requirements for urban or rural planning to reduce temperatures inside and outside buildings. For example, urban planning though increases in vegetation, green surface areas, water bodies and urban ventilation pathways could reduce any urban heat island effect.
15	Advance economic structural shifts towards industries involving non- outdoor work, less energy-intensive work	Regulatory & infrastructural	govt	М	н	√	Decrease of activity in sectors exposed to high outdoor temperatures (and increase of activity in sectors where work occurs indoors in lower temperatures) reduces exposure of workers to high temperature conditions.
16	Expanding the use of information and communications technologies	Regulatory & infrastructural	govt	М	L		Expanded use of ICT would lead to decreased work-intensity of jobs, and facilitate a shift towards indoor and/or less energy-intensive work.
17	Promote modernized agricultural technologies	Regulatory & infrastructural	govt	М	М		Policies that enable a shift towards increased mechanisation of agricultural activities, or increased capital-to-labour ratios in the agriculture sector.
18	Migration assistance	Regulatory & infrastructural	govt	L	Μ		This response aims to assist the individual- or firm-level response of moving from areas with high temperatures to areas of low temperatures (discussed below).
19	Early heat warning stations	Regulatory & infrastructural	govt / firm	н	М	~	Early warning stations would raise awareness of high temperatures among workers, enabling them to adjust their working hours, or reduce their labour supply or intensity to avoid negative impacts on health.
20	Education and awareness campaigns (on risk of heat)	Regulatory & infrastructural	govt / firm	Н	L	✓	These measures would increase general awareness of risks that working in high temperatures pose to human health, encouraging workers to reduce their labour supply or intensity to avoid negative impacts on health, and training individuals on how to use cooling measures (such as building cooling systems, reducing sources of internal heat gains).



#	Adaptation response	Туре	Actor	Feasibility	Impact potential L / M / H	Shortlisted	How this response operates
21	Worker practice and monitoring programs (e.g. rest, scheduling and acclimatization regimes, bio-physical monitoring and other related measures)	Regulatory & infrastructural	govt / firm	М	L	1	These business-level measures would enable monitoring of workers activities and encourage activities to reduce the impact of high temperatures on human health. Programmes that encourage acclimatization could reduce levels of heat stress associated with a given temperature level.
22	Occupational choice	Behavioural	ind	н	н	~	Individuals may choose to switch between occupations to reduce their exposure to high temperature working conditions.
23	Changing working hours	Behavioural	firm / ind	М	н	1	Individuals or groups alter the hours they work to better cope with high temperatures. This could include changing working hours within the working day to working during cooler periods in the day, or distributing working hours across additional days (i.e. days that were previously non-working days) to reduce the hours worked in high temperature conditions on a given day.
24	Changed choice of clothing	Behavioural	ind	н	L		Heavy clothing can increase the effective intensity of work tasks. Changing clothing to lighter choices can therefore reduce the effective intensity of work in different sectors, and thus reduce the impact of temperatures on productivity loss.
25	Individual heat-reducing activities	Behavioural	ind	н	М	×	Individuals can take actions to reduce their body temperatures, such as consuming cold beverages, taking cooling shower breaks, using individual cooling devices (fans).
26	Migration (away from hot areas)	Behavioural	ind	L	н		Individuals may relocate away from areas of higher temperatures to areas of lower temperatures to reduce the productivity loss due to higher temperatures.
27	Change firm location / relocate facilities	Behavioural	firm	L	н		Businesses may relocate operating locations from areas of higher temperature to areas of lower temperature to reduce the labour productivity loss due.
28	Spatial zoning	Behavioural	firm	М	М		This measure involves using different areas within buildings to avoid parts of buildings that receive direct solar radiation during the day. This could be complemented by the provision of cooling areas (such as 'cool rooms') to enable workers to cool down for a short period during the working day (avoiding full workspace cooling).
29	R&D in reducing adaptation flow cost (energy cost) for air conditioning	R&D	govt	М	L		Investments in understanding how to reduce the energy cost of using air conditioning, to enable greater flow use of this adaptation measure.
30	R&D in reducing adaptation stock cost (AC units) for air conditioning	R&D	govt	М	L		Investments in understanding how to reduce the installation cost of air conditioning, to enable greater stocks of (and ultimately greater flow use of) this adaptation measure.

from the British people

#	Adaptation response	Туре	Actor	Feasibility L / M / H	Impact potential L / M / H	Shortlisted	How this response operates
31	R&D in reducing heat output of indoor devices (e.g. electronics, ovens, furnaces)	R&D	govt	М	L		Investments in understanding how to reduce the heat output from indoor devices, to enable greater reductions of internal sources of heat.

Source: Vivid Economics



Appendix F – Description of Adaptation Options

In this section we include an overview assessment for each of the technical, infrastructural and regulatory, and behavioural response options included in the short-list. These summaries use a standard template which includes:

- a description of the main mechanism through which the measure reduces the impact of heat on labour productivity;
- the contextual factors that are most relevant when considering implementation (e.g. flexibility, energy costs, urban vs rural etc.);
- robustness to uncertainty, helping to identify those measures that may be close to fulfilling 'no-regrets' and in some contexts should be prioritised in the near term;
- direct costs and benefits, co-benefits and indirect costs as described in Section 8.

A template is completed to describe all options on the shortlist:

#1.	air conditioning	p. 79
#2.	increased ventilation	p. 81
#3.	external shading	p. 83
#4.	internal shading	p. 85
#5.	reduced internal gains	p. 87
#6.	increased albedo	p. 88
#7.	green roofs	p. 90
#8.	mechanisation	p. 92
#9.	outdoor shade	p. 94
#10.	climate smart municipal design	p. 95
#11.	structural economic shifts	p. 97
#12.	early heat earning systems	p. 99
#13.	education and awareness campaigns	p. 101
#14.	worker practice and monitoring programs	p. 102
#15.	occupational choice	p. 104
#16.	changing working hours	p. 107
#17.	individual heat-reducing activities	p. 109





#1. Air conditioning

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Reduces indoor temperatures through cooling air and re-circulating into room Level of cooling and timing of cooling fully selectable by user
	Applies to all indoor workers, across all sectors
Contextual	Applies across all intensity levels – primarily benefits medium or low intensity workers (because indoor workers tend not to be high intensity)
factors	Applies more to urban areas due to the reliance on an electricity grid
	Feasible at multiple scales – room, building, city, national levels, but not individual level
	Low regrets option in countries with high base or peak temperatures
Robustness & uncertainty	However, externalities of use (see climate, health costs below) implies a disconnect between private and social desirability
	Flexible under different future outcomes (e.g. high or low temperature increases, high or low energy costs)

Direct Costs and Benefits

Reducing productivity losses	Air conditioning (AC) is flexible, and can deliver flexible cooling on demand limitations on cooling arise from cost and energy supply constraints, and technical capacity of individual units (compared to the area they are required to cool)
Fixed and	Fixed installation costs – variable by size of unit, on order of USD 3,780 to USD 7,560 per AC unit (Economic Commission for Latin America and the Caribbean, 2011)
variable	Capital constraints may limit private take-up given high up-front costs
costs	Maintenance costs are non-trivial. Operational costs vary depending on energy costs, size of AC unit, size of room being cooled, efficiency of unit, desired temperature level sought

Co-benefits and indirect costs

Climate:

- Increases energy usage for expanded air conditioning use may increase GHG emissions (dependent on energy source and grid efficiency)
 Hydrofluorocarbons (HFCs) used for AC cooling are potent GHGs (one
- Hydrofluorocarbons (HFCs) used for AC cooling are potent GHGs (one thousand times as potent as CO₂)
 Increases temperatures outside buildings using air conditioning, increasing
- Increases temperatures outside buildings using air conditioning, increasing the need for adaptation measures



Socio-economic:

- Expanded use of AC may create 'summer fuel poverty' that disadvantages firms that cannot afford to operate the measure, which may be particularly felt among small and medium enterprises
- Increases temperatures outside buildings using air conditioning, inducing labour productivity loss or requiring surrounding buildings to conduct more of their own mechanical cooling

Health:



- Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from occupational injuries, reduced mental health problems from heat exhaustion
- Increases temperatures outside buildings using air conditioning, causing negative heat outcomes for users of outdoor spaces and exacerbating urban heat island effects





#2. Increased ventilation

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Flow of air through a building increases the rate of evaporation of sweat Only effective if indoor temperature greater than outdoor temperature
Contextual factors	Applies to all indoor workers, across all sectors, urban and rural
	Applies across all intensity levels – primarily benefits medium or low intensity workers (because indoor workers tend not to be high intensity)
	Feasible at multiple scales –building, city, national levels, but not individual or room level
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures
	Inflexible as ventilation channels must be fitted into buildings. The channels should, however, use a 'door' to adjust the flow of ventilation

Direct Costs and Benefits

Reducing productivity losses	Operative temperature in a factory with a ventilated roof was 4°C lower than in a factory with a single roof (Susanti, Homma, & Matsumoto, 2011a)
Fixed and variable costs	Low capital and operational costs (Kang & Lee, 2008) – retrofitting costs are much greater
	Opportunity cost of extra space required above rooms for ventilation channels in a new building

Co-benefits and indirect costs

Climate:



- During summer with air conditioning set at 26°C, ventilation achieved a 50% reduction in artificial cooling (air conditioning) to achieve same temperature, reducing release of greenhouse gases (Susanti, Homma, & Matsumoto, 2011b)
- Reduces the effectiveness of artificial cooling if indoor air is cooler than outside, which increases GHG emissions from energy use

Socio-economic:

- Reduces need for artificial cooling which decreases expenditure on energy use
- Increases need for artificial cooling if indoor air is cooler than outside which
 increases expenditure on energy use







- Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion
- Flow of fresh outdoor air positively affects mental well-being
- If outside air is polluted, allowing this air to flow into buildings worsens lung health

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#3. External shading

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Blocks sunlight from entering a building and so reduces internal temperature
Contextual factors	Applies to all indoor workers, across all sectors, urban and rural
	Applies across all intensity levels – primarily benefits medium or low intensity workers (because indoor workers tend not to be high intensity)
	Feasible at multiple scales – room, building, city, national levels, but not individual level
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures
	Flexible as shades can be opened and closed at will

Direct Costs and Benefits

Reducing productivity losses	Eliminating direct sunlight exposure is equivalent to a 3°C reduction in temperature during daylight hours (Kjellstrom et al., 2014)
Fixed and variable costs	Installation costs for a $110m^2$ detached residence in the UK are estimated at £1000-£1200 for retrofitting and £900-£1080 for a new build (Davis Langdon & Ecofys, 2011)
	Costs increase incrementally as building size increases (Davis Langdon & Ecofys, 2011)

Co-benefits and indirect costs



Climate:

- Reduces need for artificial cooling which decreasesGHG emissions from energy use
- May increase the need for artificial lighting by reducing the sunlight entering • through a window, which increases GHG emissions from energy use



Socio-economic:

- Reduces need for artificial cooling which decreases expenditure on energy use
- Increasesneed for artificial lighting which increases expenditure on energy use







Health:

• Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion





#4. Internal shading

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Blocks sunlight from entering a building and so reduces internal temperature
Contextual factors	Applies to all indoor workers, across all sectors, urban and rural
	Applies across all intensity levels – primarily benefits medium or low intensity workers (because indoor workers tend not to be high intensity)
	Feasible at multiple scales – room, building, city, national levels, but not individual level
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures Flexible as shades can be opened and closed at will

Direct Costs and Benefits

Reducing productivity losses	Eliminating direct sunlight exposure is equivalent to a 3°C reduction in temperature during daylight hours (Kjellstrom et al., 2014)
	Internal shading halts sunlight after it has already entered a building, which reduces its effectiveness relative to external shading
Fixed and variable costs	Installation costs for a $110m^2$ detached residence in the UK are estimated at £171- £228 for retrofitting and £154-£205 for a new build. Costs increase minorly as building size increases (Davis Langdon & Ecofys, 2011)

Co-benefits and indirect costs

Climate:

- Reduces need for artificial cooling which decreases GHG emissions from energy use
- May increase the need for artificial lighting by reducing the sunlight entering through a window, which increases GHG emissions from energy use



Socio-economic:

- Reduces need for artificial cooling which decreases expenditure on energy use
- Increasesneed for artificial lighting which increases expenditure on energy use



Health:

• Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion





#5. Reduced internal gains

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Reducing use of heat-outputting devices (e.g. electronics, ovens, furnaces) eliminates internal source of heat in buildings
Contextual factors	Applies to all indoor workers in environments where devices release heat, urban and rural
	Primarilyrelevantin industry environments (e.g. furnaces)
	Feasible at multiple scales – room, building, city, national levels, but not individual level
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures
	Flexible if upgrades are factored into equipment lifecycle replacement decisions, inflexible if investment in current best-available technology precludes subsequent investment in more efficient technologies

Direct Costs and Benefits

Reducing	Temperature reduction depends on working conditions
productivity	WBGT reductions on order of 1°C to 3°C WBGT possible in moving from gas to
losses	electric kitchen equipment in most kitchen environments (Matsuzuki et al., 2011)
Fixed and variable costs	Costs highly variable dependent on degree of efficiency sought, whether equipment upgrades are factored into existing upgrade schedules or if retro-fitting is required

Co-benefits and indirect costs



Climate:

- High-efficiency equipment decreases GHG emissions from energy use
- Reduces need for artificial cooling which decreases GHG emissions from energy use



Socio-economic:

- High-efficiency equipment decreases expenditure on energy use
- Reduces need for artificial cooling which decreases expenditure on energy use

Health:

• Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion



#6. Increased roof albedo

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Reduces indoor and outdoor temperatures by absorbing less solar energy – higher albedo than traditional roofs (Foster et al., 2011)
	Two effects: 1) Internal impact where less heat is transferred into the building; 2) External impact where the air around a green roof remains cooler, which reduces the Urban Heat Island effect (Claus & Rousseau, 2010)
Contextual factors	Internal benefits just for indoor workers on the top floor of a building
	External benefits of reduced Urban Heat Island apply to all urban workers across all sectors and intensities
	Feasible at multiple scales – building, city, national levels, but not room or individual level. The reflective benefits of white roofs accrue regionally across urban areas as more white roofs are added (Foster et al., 2011)
	Coordination across a city is difficult so government subsidies are required (Claus & Rousseau, 2010)
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures
	Inflexible due to its sunk cost of installation

Direct Costs and Benefits

Reducing productivity losses	Can reflect 60% of direct solar radiation, versus 10%-20% reflected by traditional roofs, thereby reducing internal heat (Lundgren & Kjellstrom, 2013)
	Can reduce roof temperature increases (relative to air temperature) by 20-50°C: conventional roofs can be 31-55°C hotter than air temperature, cool roofs tend to stay within 6-11°C of the background temperature (Foster et al., 2011)
	Can reduce internal temperatures by 1.5-3.5°C in some contexts – with white enamel paint able to reduce internal temperatures by 3.1°C during hottest part of day (Khan, Malik, & Rehman, 2014)
Fixed and variable costs	Cost of white roofs installation is comparable to that of conventional roofs, roughly $0.2 - 6 / m^2$ more expensive (<10% of total cost) (Foster et al., 2011; Khan et al., 2014)
	Retrofitting is more expensive

Co-benefits and indirect costs

Climate:

- Reduces need for artificial cooling which decreases GHG emissions from energy use (Foster et al., 2011)
- Increases need for artificial warming in winter which increases GHG emissions from energy use (Foster et al., 2011)



Socio-economic:

- Reduces need for artificial cooling which decreases expenditure on energy use – estimated in the US at \$2.35/m²(Foster et al., 2011)
- Increases need for artificial warming in winter which increases expenditure on energy use (Foster et al., 2011)

Health:



- Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion
- Reduces extreme Urban Heat Island during heatwaves which lowers risk of mortality from heat stress for vulnerable citizens (Altvater et al., 2012)





#7. Green roofs

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Reduces indoor and outdoor temperatures by absorbing less solar energy – higher albedo than traditional roofs (Foster et al., 2011)
	Two effects: 1) Internal impact where less heat is transferred into the building; 2) External impact where the air around a green roof remains cooler, which reduces the Urban Heat Island effect (Claus & Rousseau, 2010)
Contextual factors	Internal benefits just for indoor workers on the top floor of a building
	External benefits of reduced Urban Heat Island apply to all urban workers across all sectors and intensities
	Feasible at multiple scales – building, city, national levels, but not room or individual level. The reflective benefits of green roofs accrue regionally across urban areas as more green roofs are added (Foster et al., 2011)
	Coordination across a city is difficult so government subsidies are required (Claus & Rousseau, 2010)
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures
	However, water availability and irrigation potential may be an issue under future climate change, limiting green roof effectiveness
	Inflexible due to its sunk cost of installation

Direct Costs and Benefits

Reducing productivity losses	50% city-wide green roof coverage associated with a 1°C temperature reduction in Toronto (Banting et al., 2005)
	75% green roof coverage on flat-roofed buildings associated with a 0.4°C temperature reduction in New York City (Rosenzweig et al., 2006)
Fixed and variable costs	Direct installation costs - retrofitting a green roof on top of an existing grey roof - are estimated at $32-42 \notin m^2$ in developed countries (Altvater et al., 2012)
	Capital constraints may limit private take-up given high up-front costs
	Annual maintenance costs are similar to traditional roofs at 0.18-1 €/m²(Altvater et al., 2012; Claus & Rousseau, 2010)

Co-benefits and indirect costs

Climate:



- Reduces need for artificial cooling which decreases GHG emissions from energy use (Foster et al., 2011)
- Provides insulation in winter which reduces need for artificial warming, decreasing GHG emissions from energy use (Foster et al., 2011)



Socio-economic:



- Reduces need for artificial cooling and warming which decreases expenditure on energy use – a 1000m² surface with a green roof would deliver savings of roughly \$400 per year in heating costs and \$250 per year in cooling costs (Foster et al., 2011)
- Green roof lifespan can be double the 25 year lifespan of a traditional roof due to the protection from UV and weather provided by the layer of shrubbery(Claus & Rousseau, 2010)
- The thickness of green roofs muffles urban noise, reducing internal noise level by 20-25dB (Claus & Rousseau, 2010)

Environmental:

- Promotes biodiversity (Altvater et al., 2012)
- Reduces rainwater flowing into sewers during flash floods (Claus & Rousseau, 2010)

Health:



- Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion
- Reduces extreme Urban Heat Island during heatwaves which lowers risk of mortality from heat stress for vulnerable citizens (Altvater et al., 2012)
- Improves the local air quality by absorbing toxins (CO₂, O₃, NO_x, Particulates) in the air (Claus & Rousseau, 2010; Foster et al., 2011)
- Green spaces in cities improve mental health(Claus & Rousseau, 2010)





#8. Mechanisation

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Reduces level of effort required by workers in labour-intensive industries, which reduces heat stress e.g. tractors on farms, machines in factories
Contextual	Applies to all manual workers in high-intensity industries e.g. farming, manufacturing, construction
	Does not apply to low-intensity work e.g. office-based services
1401015	Applies to both urban and rural workers
	Feasible at multiple scales – individual, firm, sector, national levels
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures
	Provides significant economic co-benefits regardless of future climate change
	Flexible as machines can be turned off if they harm climate change mitigation
	Inflexible due to large up-front cost of purchase

Direct Costs and Benefits

Reducing productivity losses	Does not provide a direct temperature reduction, but rather an intensity reduction that is equivalent to a temperature change Equivalent temperature reduction depends on degree of labour intensity reduction and base temperature
	Under Kjellstrom, Lemke, Otto, Hyatt, & Dear (2014) 'Hothaps' heat-productivity relationships, moving from high to medium intensity activity is equivalent to a 2°C reduction in WBGT for most temperatures between 26°C WBGT and 38°C WBGT (equivalent to 1°C WBGT at upper and lower ends of this range)
	Moving from high to low intensity activity is equivalent to a 4°C to 5°C WBGT reduction
Fixed and variable costs	Capital investment costs vary significantly depending on the degree of mechanisation sought
	Capital constraints may limit private take-up given high up-front costs



Co-benefits and indirect costs

Climate:



- Reduces need for indoor artificial cooling which decreases GHG emissions from energy use (Foster et al., 2011)
- Increases productivity on existing farmland so there is less demand for extra woodland, which avoids deforestation and so protects natural carbon sinks
- Making and using machines produces GHG emissions

Socio-economic:

- Reduces need for indoor artificial cooling which decreases expenditure on energy use
- Increases productivity, which increases output and so citizens' economic standard of living



Environmental:

 Increases productivity on existing farmland so there is less demand for extra woodland, which preserves natural capital and biodiversity

Health:

 Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion







#9. Outdoor shade

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Protects outdoor workers from direct solar radiation Includes artificial structures and natural shades (e.g. trees)
Contextual factors	Applies to all outdoor workers, across all sectors, both urban and rural
	Applies across all intensity levels
	Feasible at multiple scales – individual, group, sector, national levels
	Works best with relatively static workers who are not covering a large geographic area
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures
	Flexible as can be adjusted to meet changing demand for shading over time. It does not require significant up-front investment

Direct Costs and Benefits

Reducing productivity losses	Eliminating direct sunlight exposure is equivalent to a 3°C reduction in temperature during daylight hours (Kjellstrom et al., 2014)
Fixed and variable costs	Capital costs vary significantly depending on the size and type of shading installed, although are relatively low

Co-benefits and indirect costs



Socio-economic:

• Protects livestock which increases agricultural productivity

Health:

• Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion



#10. Climate smart municipal design

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Reduces the Urban Heat Island effect (De Bruin et al., 2009) via higher albedo from greenery, shadowed space from trees, evaporation cooling effect, cool air lanes into the inner city (Altvater et al., 2012)
Contextual factors	Applies to all urban workers, indoor or outdoor, across all sectors and all intensities Feasible at a city scale, coordinated by local governance
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures Inflexible as requires irreversible urban planning decisions and lengthy consultation with local stakeholders

Direct Costs and Benefits

Reducing productivity losses	Trees can reduce the maximum surface temperature of roofs and walls by 11-25°C (Foster et al., 2011)
Fixed and variable costs	Opportunity cost of no economic activity on this land (Altvater et al., 2012)
	Installation cost in Chicago at \$50-\$500 per tree (Foster et al., 2011)
	Maintenance cost in Chicago at \$15-\$65 per tree per year (Foster et al., 2011)

Co-benefits and indirect costs



Climate:

- Trees shade buildings which reduces need for artificial cooling, decreasing GHG emissions by 1% per tree around houses in US cities (Foster et al., 2011)
- Green spaces absorb greenhouse gases (Altvater et al., 2012)

Socio-economic:



- Reduces need for indoor artificial cooling which decreases expenditure on energy use
- Residential property prices increase by 2-37% near to parks (Wolf, 2007)
- Increases tourism which benefits local businesses (Foster et al., 2011)
- Provides space for recreation which improves quality of life (Foster et al., 2011)

Environmental:

- Enhances biodiversity (Foster et al., 2011)
- Stores rainwater during storms to lower stress on sewers (Altvater et al., 2012) a typical medium-sized tree can intercept up to 2,380 gallons of rainfall per year (Foster et al., 2011)



Health:

- Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion
 Improves the local air quality by absorbing toxins (CO₂, O₃, NO_x,
- Improves the local air quality by absorbing toxins (CO₂, O₃, NO_x, Particulates) (Claus & Rousseau, 2010) • reduced ozone concentration leads to fewer respiratory diseases
 - reduced ozone concentration leads to fewer respiratory diseas (Foster et al., 2011)
 - increasing the urban canopy of New York City by 10% would lower ground-level ozone by about 3% (Foster et al., 2011)
 - one million additional trees in a city would lower emissions of NOx by a quarter ton per day and particulate matter by over one ton per day (Foster et al., 2011)





#11. Structural economic shifts

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Shifting workers from sectors that face high temperatures to those that face lower temperatures e.g. from agriculture into manufacturing, industry or services
	Accelerates pre-planned economic transitions in countries that are already moving away from agriculture
	Existing economic shifts (planned or autonomous) may increase exposure to heat stress e.g. a growing construction sector. In this case, this measure manages these shifts to limit heat exposure in these growing exposed sectors
Contextual factors	Applies to all outdoor workers exposed to direct sunlight, and all those in high- and medium-intensity occupations
	Feasible only at the national level (the individual equivalent is 'Occupational choice')
Robustness & uncertainty	Low regrets option in countries with high base or peak temperatures, and a high proportion of workers in high heat stress occupations (agriculture, construction, manufacturing)
	Inflexible as there exists a lag between government action and economy-wide shifts. This option is therefore unresponsive in the short-run to changes in climate forecasts

Direct Costs and Benefits

Reducing productivity losses	Shifting from outdoor to indoor work eliminates exposure to direct sunlight. Eliminating this exposure is equivalent to a 3°C reduction in temperature during daylight hours (Kjellstrom et al., 2014)
	Shifting workers from higher- to lower-intensity sectors does not provide a direct temperature reduction, but rather an intensity reduction that is equivalent to a temperature change for those workers. Equivalent temperature reduction depends on base temperature and how much work intensity changes
	Under Kjellstrom, Lemke, Otto, Hyatt, & Dear (2014) 'Hothaps' heat-productivity relationships, moving from high to medium intensity activity is equivalent to a 2°C reduction in WBGT for most temperatures between 26°C WBGT and 38°C WBGT (equivalent to 1°C WBGT at upper and lower ends of this range). Moving from high-to low-intensity activity is equivalent to a 4°C to 5°C WBGT reduction
Fixed and variable costs	No direct fixed or variable capital investment as capital is just reallocated between sectors
	The government may need to use subsidies to incentivise firms if it wishes to accelerate existing shifts



Co-benefits and indirect costs



Climate:

• Couldincrease or decrease GHG emissions depending on the relative emissions-intensity of the sectors involved in the structural shift



Socio-economic:

- Likely to increase economic output and worker standard of living
- The exact economic impact will depend on whether the shift increases employment in sectors with higher or lower output per worker, andthe new sector'spassthrough of per-worker productivity into wages

Environmental:



Couldimprove or worsen the environment depending on the relative environmental impact of the sectors involved in the structural shift - the exact impact will depend on individual sectors' use of environmental inputs and their production of pollution, but for developing countries this is likely to lead to greater damages than benefits as countries move along an environmental Kuznets curve

Health:

 Reduces heat stress across multiple health areas, including reduced risk ofheat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion





#12. Early heat warning stations

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Raises awareness of high temperatures among workers which enables them to adjust their working hours or reduce their labour supply or intensity
	Early warning stations may be combined with advice to avoid heat stress including increasing air conditioning, hydrating, dressing lightly, reducing strenuous activities (Toloo, FitzGerald, Aitken, Verrall, & Tong, 2013)
Contextual factors	Applies to allworkers, across all sectors, across all intensities. Most useful for those at risk of extreme heat stress - outdoor or high-intensity workers
	Applies mainly to urban workers because warnings are harder to transmit to rural workers
	Feasible at city, regional, or national level. Not applicable at individual or firm level
Robustness & uncertainty	Low regrets option in countries with high peak temperatures, but not with high base temperatures (warning only effective if it is rare)
	Flexible due to low upfront cost, and the ability to easily change the use and scale of the measure in response to greater certainty about the future climate

Direct Costs and Benefits

Reducing productivity losses	Avoids catastrophic cases of heat stress and encourages workers and firms to employ other heat-stress adaptations
	Its effectiveness in reducing productivity losses depends on how effectively the warning reaches at-risk workers, and how much behaviour adjusts to this warning – both highly context-specific
Fixed and variable costs	Most of the actions do not have direct monetary costs – they are part of existing jobs, conducted by volunteers, or result in delayed other tasks (Ebi, Teisberg, Kalkstein, Robinson, & Weiher, 2004)
	However, specific new public awareness measures may have significant costs – for example a 'Heatline' early warning system and associated additional medical crews have direct costs via additional wages of around \$10,000 per heat warning day (Ebi et al., 2004)

Co-benefits and indirect costs



Climate:

• Increases use of indoor artificial cooling, advised as part of the heat warning, which increases GHG emissions (Toloo et al., 2013)



Socio-economic:



- Insecure workers (those fearful of being fired) may find it tough to implement advice such as increased rest and reduced activity (Riley, Delp, Cornelio, & Jacobs, 2012)
- May decrease hourly labour productivity through greater rest and less activity advised in the heat warning(Riley et al., 2012)
- Avoided economic costs from use of medical services for example in Wisconsin, the dispatch of emergency medical services was reduced by 49%-73% on heatwave days (Toloo et al., 2013)

Health:



- Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion
- 4,400 excess deaths avoided in France in Summer 2006(Toloo et al., 2013), and 81 (out of 1094) additional deaths saved in a summer in Philadelphia (Carraro, Sgobbi, Lavoro, Eni, & Mattei, 2008)




#13. Education and awareness campaigns

Operation mechanism & contexts

Mechanism for mitigating productivity losses	Warns workers of the harm of heat stress, informs workers how to recognise the symptoms of heat stress, and instructs workers how to protect against heat stress
	Can be a bottom-up approach via community-based education, or a top-down approach via changing organisation policies (Riley et al., 2012).
	Suggested ways to protect against heat stress include drinking water frequently, taking rest breaks in the shade, and responding to early symptoms (Riley et al., 2012).
Contextual	Applies to all workers at all intensities, urban and rural
Contextual factors	Applies to all workers at all intensities, urban and rural Feasible at multiple scales – firm, city, sector, regional, national levels
Contextual factors	Applies to all workers at all intensities, urban and rural Feasible at multiple scales – firm, city, sector, regional, national levels Low regrets option in countries with high base or peak temperatures
Contextual factors Robustness & uncertainty	Applies to all workers at all intensities, urban and rural Feasible at multiple scales – firm, city, sector, regional, national levels Low regrets option in countries with high base or peak temperatures Flexible due to low upfront cost, and the ability to easily change the scale of the campaign in response to greater certainty about the future climate

Direct Costs and Benefits

Reducing productivity losses	Avoids catastrophic cases of heat stress and encourages workers and firms to employ heat-stress adaptations
	Its effectiveness in reducing productivity losses depends on how effectively the education reaches at-risk workers, and how much behaviour adjusts to this warning – both highly context-specific
Fixed and variable costs	Negligible fixed costs and low variable costs

Co-benefits and indirect costs



Socio-economic:

• Secondary purpose of campaigns to forge closer community links

Health:

• Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion



#14. Worker practice and monitoring programs

Operation mechanism & contexts

	Business-level measures that enable monitoring of workers activities and encourage adaptations to reduce the impact of high temperatures - including pre- hire screening, pre-start acclimatisation, risk training, on-the-job monitoring
Mechanism	<i>Heat Tolerance Screening</i> uses a medical assessment to filter high-risk workers, based on the worker's medication, underlying conditions, alcohol habits, cardiovascular fitness, body mass index, and blood pressure (Jay & Kenny, 2010)
	Acclimatisation improves the body's tolerance and dissipation of heat. Workers spend 4 to 14 days in a high-heat environment to 'train' sweat glands and to establish behavioural habits such as drinking more frequently, breaking more regularly, and pacing their effort (Jackson & Rosenberg, 2010)
for mitigating productivity losses	<i>Training</i> emphasises the importance of heat stress and the firm's mitigation efforts (Bernard & Cross, 1999).
	<i>Monitoring</i> uses heat stress meters, ingestible telemetric pills, or heart rate tracking to give managers sensory information on individual workers (Jay & Kenny, 2010).
	Heat stress mitigation techniques include supply of individual fans and plentiful water provision (Bernard & Cross, 1999)
	Some measures may have ambiguous outcomes for labour productivity - for example regular breaks in air-conditioned rooms and lowered task intensity when heat is high (Bernard & Cross, 1999) would only lead to a net increase in labour productivity if the break time and reduced work intensity lead to smaller losses in output than would be observed under continuous work at normal intensity levels
	Applies to all workers, across all sectors, urban and rural
Contextual	Particularly useful for high-intensity workers
factors	Feasible at multiple scales – firm, city, sector, regional, national levels, but not individual level
	Low regrets option in countries with high base or peak temperatures
Robustness & uncertainty	Flexible due to low upfront cost, and the ability to easily change the scale of the program in response to greater certainty about the future climate
	Complementary to other adaptations

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Direct Costs and Benefits

Reducing productivity losses	Acclimatisation to high temperatures increases the effective temperature level at which heat stress leads to lost labour productivity. For example, regulatory threshold limit values for labour in Canada indicate that acclimatisation increases the threshold at which productivity losses occur by 2°C to 3.5°C WBGT (Jay & Kenny, 2010). However, these benefits only accrue to workers that were not previously acclimatised
	The effectiveness of training and monitoring in reducing productivity losses depends on how effectively the education reaches at-risk workers, and how much behaviour adjusts to this warning – both highly context-specific
Fixed and variable costs	Firms pay upfront costs in screening and training through staff time spent administering programmes or the costs of engaging external contracts to manage these programs
	For acclimatisation, firms incur an opportunity cost of time the worker spends acclimatising
	For monitoring, firms can incur high ongoing costs for monitoring technologies to observe worker heat stress

Co-benefits and indirect costs



Climate:

• Using personal fansuses more energy which increases GHG emissions



Socio-economic:

- Heat stress coping strategies such as using personal fans increase energy expenditures
- Workers with pre-existing health conditions may struggle to find a job if they fail to pass screenings

Health:

 Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion







#15. Occupational choice

Operation mechanism & contexts

	Individuals may choose to switch between occupations to reduce their exposure to high temperature working conditions
Machanism for mitigating productivity lasses	Reduces temperature through two primary mechanisms: moving to an occupation that is less exposed to high temperatures (for example, from outdoor to indoor) and moving to a lower intensity job that causes less heat stress for a given temperature level (for example, from manufacturing to services)
Mechanism for miligating productivity losses	Changing occupation may allow workers to use other adaptation measures - for example, moving to an office job from outdoor work allows the worker to benefit from air conditioning
	Changing occupation may allow workers more flexibility over their working hours to avoid the midday heat – for example, although moving into agriculture would increase exposure, it would allow greater flexibility over working hours
Contextual factors	Primarily applies to workers in sectors that are exposed to direct sunlight or are in high- or medium- intensity occupations, urban and rural
	Feasible only at the individual level (the sector/national equivalent is 'Structural economic shifts')
	Low regrets option in countries with high base or peak temperatures
Robustness & uncertainty	This is primarily an autonomous measure, and in principal can be flexibly adjusted in response to increased evidence on level of climate impacts. For example, an individual can switch occupations flexibly based on the evidence of future heat exposure levels. However, in practice barriers to and costs of switching may limit ability to move between occupations

Direct Costs and Benefits

	Shifting from outdoor to indoor work eliminates exposure to direct sunlight. Eliminating this exposure is equivalent to a 3°C reduction in temperature during daylight hours (Kjellstrom et al., 2014)
Reducing productivity losses	Shifting workers from higher- to lower-intensity sectors does not provide a direct temperature reduction, but rather an intensity reduction that is equivalent to a temperature change for those workers. Equivalent temperature reduction depends on base temperature and how much work intensity changes
	Under Kjellstrom, Lemke, Otto, Hyatt, & Dear (2014) 'Hothaps' heat-productivity relationships, moving from high to medium intensity activity is equivalent to a 2°C reduction in WBGT for most temperatures between 26°C WBGT and 38°C WBGT (equivalent to 1°C WBGT at upper and lower ends of this range). Moving from high-to low-intensity activity is equivalent to a 4°C to 5°C WBGT reduction
	No direct fixed or variable cost as labour is just reallocated between sectors
Fixed and variable costs	A worker may face switching costs of changing occupation (e.g. a week unpaid between jobs), and will lose job-specific human capitalmeaning a potentially lower wage in the new job
Co-benefits and indirect costs	

Socio-economic:



- Workers may face periods of unemployment as they search for new positions, which will reduce economic output and lower their income
- At a large scale, changes in occupational structure may affect economic output at a sectoral or national level – the exact impact will depend on whether individuals move into or away from occupations with higher economic output per worker, and whether short term occupational changes contribute to a large scale structural shift in the economy



Health:



 Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion



#16. Changing working hours

Operation mechanism & contexts

	Individuals or groups alter the hours they work to reduce hours worked in high temperatures
Mechanism for mitigating productivity losses	Options are starting and finishing earlier each day, implementing a split working day with a long lunch (e.g. Spanish siesta), shifting a proportion of weekly work to cooler parts of a non-working day (e.g. weekend), or seasonal adjustments to increase work in winter and reduce hours during summer (for example, working 1 extra hour daily during 9 months of the year, then reducing daily working hours by 3 hours during the remaining 3 months)
	The optimal change in hours will be highly context specific
Contextual factors	Applies to all workers, across all sectors, across all intensities, urban and rural
	Feasible at all scales – individual, firm, city, sector, regional, national levels
	Feasibility of broad application at sector or national level depends on government ability to effectively alter social customs around daily, weekly and seasonal working patterns
	Low regrets option in countries with high base or peak temperatures
Robustness & uncertainty	In principle, working hours can be flexibly adjusted in response to increased evidence on level of climate impacts. In practice, adjustments to working hours may be constrained by social boundaries for acceptable variations to working patterns. Given the potential for social resistance to change, it may prove challenging to further adjust hours once a new equilibrium is reached following a governmental intervention to influence working hours
Direct Costs and Benefits	
Reducing productivity losses	Reductions in productivity loss depend significantly on the level of change in working hours or patterns, the number of hours that are subject to some productivity loss, and the degree of productivity loss in the hours that are no longer worked versus the degree of loss felt in new hours worked.
	in some contexts through the individual timing of vacations in high temperature periods.



Fixed and variable costs	awareness-raising programmes, or through implementing regulations of working hours. Given a high degree of variability in the extent of such actions, direct costs may vary from zero costs to very high costs.
Co-benefits and indirect costs	
	Climate:
	 Adjusted working hours away from high- temperature periods would reduce the demand for air conditioning, which would decrease GHG emissions
	Socio-economic:
	 Adjusted working hours away from high- temperature periods would reduce the demand for air conditioning, which would decrease energy expenditure Adjusted working patterns could improve or reduce the quality of non-working leisure time, depending on the working hours change introduced – for example, changes that lead to additional leisure time during summer months would be beneficial, whereas 'split shifts' would reduce quality non-working leisure time in the evenings
	Health:
- 4	 Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion Shift work (i.e. not during normal working hours) is associated with increased physical and mental health damages, including reduction in quality and quantity of sleep,

This measure does not include any direct costs at

Direct costs at the sectoral or national levels would be incurred through government education and

fatigue, anxiety, depression, adverse cardiovascular effects and gastrointestinal

disorders (Harrington, 2001)

the individual or firm level.

: vivideconomics





#17. Individual heat-reducing activities

I Individuals can take actions to reduce their body temperatures, such as consuming cold drinks, taking cooling shower breaks, using individual cooling devices (including fans or cooling clothing, such as 'ice vest systems') (Bernard & Cross, 1999) Some measures may have ambiguous outcomes for Mechanism for mitigating productivity losses labour productivity - for example regular breaks and lowered task intensity when heat is high (Bernard & Cross, 1999) would only lead to a net increase in labour productivity if the break time and reduced work intensity lead to smaller losses in output than would be observed under continuous work at normal intensity levels Applicability of measures varies according to different contexts - some measures benefit all workers regardless of sector of work, location of work or intensity of work, such as cold beverage consumption or cooling clothing. Other measures may only be applicable to indoor workers (such as Contextual factors use of fans), or workers with access to specific facilities (for cooling shower breaks) Feasible only at the individual level (the firm-level equivalent is 'Worker practice and monitoring programmes') Low regrets option in countries with high base or peak temperatures Robustness & uncertainty Flexible due to the ability to easily change the amount of heat-reducing activity on a daily basis **Direct Costs and Benefits** The effectiveness in reducing productivity losses depends on how much heat stress the worker faces, how much other adaptation is already present in their Reducing productivity losses work environment, and how much individual adaptation they decide to carry out - all highly context-specific Low but repeated costs (e.g. buying a cold drink Fixed and variable costs each day)







Co-benefits and indirect costs

Health:	
•	Reduces heat stress across multiple health areas, including reduced risk of heat stroke, heat exhaustion and death, reduced damage of vital organs (inc. heart overload, kidney damage), fewer injuries from accidents and occupational injuries, reduced mental health from heat exhaustion



Appendix G – Model Specification

This appendix summarises the modelling approach to estimate the potential impact of temperature increases on labour productivity. First the principles of the approach taken and data used are set out, then a detailed description of the model, including assumptions made, is provided.

Principles of the modelling framework

The model is a simple representation of how current and future temperatures will affect labour productivity and the national economy, and is flexible and adaptable for the end user. It expands on work in this area to provide a framework that can be easily applied to new contexts using data that is for the most part publicly available.

The spreadsheet-based model follows a core structure with three main sections:

- 1. <u>User-defined inputs and assumptions.</u> These tabs allow the user to define core parameters for the model, and enable scenario (and potentially simulation) analysis.
- 2. <u>*Raw input data*</u>. Raw data is kept in separate tabs, drawing primarily on publicly available data which could be extended to other country contexts.
- 3. <u>*Processing tabs and results.*</u> All model calculations are separated into a series of processing tabs, and output tabs that present summary model outputs.

The approach builds on established work in this area; in particular frameworks used in Kjellstrom et al.'s global assessment of the impacts of climate change on labour productivity (Kjellstrom et al., 2014) and Costa et al.'s methodology for assessing temperature increase impacts on labour productivity in cities (Costa et al., 2016a). It combines key elements of these approaches, and represents the first publicly-available tool to flexibly and transparently estimate the labour productivity and economic implications of heat stress on the labour force.

The model provides users with a number of outputs to characterise the impacts of increasing temperatures on labour productivity:

- the proportion of productive time and number of work days lost due to current and future heat stress annually across different sectors of the economy in 2015, 2030 and 2050;
- the cost of this lost productive time in terms of reduced economic output in 2015, 2030 and 2050, both by sector and for the overall economy.

The model is made up of three nested elements that combine to provide a projection of the future labour productivity costs due to climate change. These three components, also shown inFigure 25, are combined to generate the model outputs for each country:

1. *hour-by-hour temperature profiles* for representative days for each of the twelve months in three time periods: baseline, 2030 and 2050;





- 2. a *model of 'effective' labour supply* for different sectors of the economy for 2015 (based on baseline temperatures), 2030 and 2050, which feeds into the main model of the economy;
- 3. a *simple multi-sectoral national economic model* that incorporates the impacts of high temperatures on labour supply to project lost national and sectoral output in 2015, 2030 and 2050 due to current climate and future climate change.

Figure 25. The modelling uses temperature changes to estimate effective labour supply under climate change as an input to a stylised national economy



Source: Vivid Economics

Data used in the model

Data is drawn largely from commonly available international datasets wherever possible to make it easy to apply the model to new contexts. Key sources include:

For modelling daily temperature profiles:

 country-level temperature projection based on the Coupled Model Intercomparison Project's (CMIP) latest model comparison exercise, CMIP5, made available through the World Bank's Climate Change Knowledge Portal;





 country-level relative humidity data based on the NASA POWER (Prediction of Worldwide Energy Resource) Climatology Resources for Agroclimatology assessment of average relative humidity from 1983, available for one degree by one degree grid squares.

For modelling the effective labour supply under different climate conditions:

- the High Occupational Temperature Health and Productivity Suppression (Hothaps) relationship between temperature and labour productivity, as set out in Kjellstrom et al. (2014);

For modelling the national economy:

- the Global Trade Analysis Project database for current capital stock shares by sector;
- UN National Accounts Official Country Data to project growth in the total capital stock;
- the ILO Key Indicators of the Labour Market for current employment shares by sector and total employment, and for projected total employment in 2030 and 2050;
- UN National Accounts Official Country Data for the present day Gross Value Added (GVA) per sector, for calibrating the model parameters;

Modelling methodology

Modelling the national economy

The national economy is simplified to a model made up of seven sectors, and national output is the sum of output in each sector, as shown in Figure 26. The sectors are: 'Agriculture'; 'Manufacturing'; 'Construction'; 'Other industry'; 'Wholesale and retail trade'; 'Transport, storage and communication'; and 'Other services'.²² These provide variation in conditions that will be affected by heat differently – i.e. indoor vs outdoor, and low/medium/high intensity work – within the limits of available data needed on sectoral economic output and employment.

²² This approach broadly follows the approach taken by based on Costa, Floater, Hooyberghs, Verbeke, & De Ridder (2016).





Figure 26. We use a multi-sector model of production to assess output

$$Y_{c,t} = \sum_{s=1}^{n} A_{s,c} \Big[\theta_s \big(a_{K,s} K_{c,s,t} \big)^{\gamma_s} + (1 - \theta_s) \big(a_{L,s} \big(WBGT_{c,s,t} \big) L_{c,s,t} \big)^{\gamma_s} \Big]^{1/\gamma_s} \Big]^{1/\gamma_s}$$

Note: c = country, t = time period, s = sector

A_{s,c} represents sectoral total factor productivity

 $K_{s,c,t}$ represents capital inputs per sector, $L_{s,c,t}$ represents raw labour inputs per sector

 Θ_s represents the sectoral share of capital in the production function, $(1 - \Theta_s)$ represents the sectoral share of labour in the production function

 $a_{K,s}$ is the sectoral productivity of capital, assumed to be equal to 1 for all sectors

 $a_{L,s,t}$ is the sectoral effectiveness of labour supply, a function of the temperature (measured in WBGT)

WBGT_{c.s.t} is the sectoral WBGT, which varies by country, sector and time period

 $\rho_s = 1/(1 - \gamma_s)$ is the sectoral degree of elasticity of substitution, used as an input to determine γ_s , determining how

capital and labour can be substituted each sectoral production function

Source: Vivid Economics, based on Costa, Floater, Hooyberghs, Verbeke, & De Ridder (2016)

For 2030 and 2050, the model is run using the effective labour supply under climate change, and the counterfactual effective labour supply without future climate change. These model runs provide a number of outputs for each time period:

- the proportion of the total labour supply rendered ineffective due to heat stress, by sector and for the whole economy;
- the total loss of output due to heat stress, in absolute and per capita terms, by sector and for the whole economy.

To isolate the productivity impacts, only 'effective labour supply' varies with temperature levels. All other inputs to the model are not sensitive to climate change scenarios. Specifically:

- future employment for each sector is projected based on ILO projections for the total labour force and current shares of employment by sector for each country.;
- total capital stock is projected forwarding using historic compound annual growth rates per country from 2004 to 2014, which converge to the worldwide historic average capital growth rates by 2050;
- each sector's share of the capital stock is held constant for each country;
- the shares of capital and labour in each sector's production function (which vary by country), and the intra-sectoral elasticities of substitution between labour and capital (which are the same for all countries), are held constant across all time periods;
- there is no automatic rebalancing of labour and capital across sectors of the economy, i.e. the model does not include any inter-sectoral substitution of labour or capital.

Modelling effective labour supply

To run the model as described above, for each time period and each sector of the economy we calculate the function $a_{L,s,t}$, denoting the effectiveness of labour for each sector. We calculate this function by considering the environmental and working conditions in the different sector contexts.







For each sector, we make a number of simplifying assumptions around working conditions. In

particular, we make assumptions about the share of work that is undertaken outdoors vs indoors and the intensity level of employment in different sectors of the economy:

- all work conducted in the 'agriculture' and 'construction' sectors is carried out outdoors in direct sunlight.
- employment in all other sectors is conducted indoors.
- 'agriculture' and 'construction' sectors represent 'high' intensity work,
- 'manufacturing' and 'other industry' sectors represent 'moderate' intensity,
- all other sectors are characterised by 'low' intensity.²³

We assume all workers wear light clothing that does not affect the intensity level of work. Heavier clothes make people more susceptible to higher temperatures, affecting work intensity and productivity. For simplicity, we assume all workers are already wearing light clothing that does not increase the effective intensity of work, in line with the approach taken in Kjellstrom et al. (2014).

For each country, we assume set working hours that apply to all workers in the country, but which can differ by sector. The default assumption is that workers in all countries and sectors work a five hour shift in the morning (8am to 1pm) and a three hour shift in the afternoon (2pm to 5pm). However, we can define these working hours for each sector and country on a flexible basis – which may be important both to accurately represent losses in the baseline, and as a potential adaptation option.

For each sector, month and time period, we combine models of productivity loss with WBGT increases to determine hourly and overall effectiveness of labour. We apply the Kjellstrom, Lemke, Otto, Hyatt, & Dear (2014) 'Hothaps' models of percentage loss for three different work intensities in hourly work capacity to determine hourly percentage productivity loss. The 'Hothaps' response functions are used as they represent the most recent functions based on broad evidence from supporting studies including experimental data. Some of the curves active at lower temperatures result from 'standards'-based response functions (as produced by ISO), which may overstate the direct 'economic' impact of high temperatures which is better estimated by experimental studies.²⁴

The hourly productivity loss estimates are combined with assumptions on working conditions and working hours to determine an overall daily measure of the effectiveness of sectoral labour supply. The resulting values, $a_{L,s,t}$, represent the effective labour supply as a percentage of the total potential labour supply. The *a*_{L,s,t} values are calculated for each sector and in each of the three time periods.





²³ Our modelled work intensity by sector combines the approaches taken in Kjellstrom, Lemke, Otto, Hyatt, & Dear (2014) and Costa, Floater, Hooyberghs, Verbeke, & De Ridder (2016),

²⁴ On the other hand, the standards based studies may better represent the full range of the impacts of higher temperatures on human wellbeing (e.g. including health effects), described in Section 2.3. For consistency throughout this study we draw primarily on the results from the experimental studies, which document observed reductions in productivity resulting from temperature increases.



Figure 27. **Productivity : heat relationships employed in Vivid model**

Source: Vivid Economics model and sources in Figure 3

Modelling temperature profiles

We extract national temperature profiles for turn of the century, 2030 and 2050 from the World Bank's Climate Change Knowledge Portal. Monthly average maximum, mean, and minimum temperatures are taken from the WB portal (World Bank, n.d.) for each snapshot in time. The 'baseline' values are based on temperatures over the period from 1986 to 2005, temperatures for '2030' are based on projections for the period from 2020 to 2039, and temperatures for '2050' are based on projections for the period from 2040 to 2059.

The future projections are based on data from climate models used by the Intergovernmental Panel on Climate Change (IPCC). For each country and temperature variable, we extract values for 16 model runs across each of four future scenarios, specifically the four Representative Control Pathways (RCPs) used in IPCC's Fifth Assessment Report (AR5). The scenarios represent different potential paths for future emissions levels based on different levels of global economic development and different levels of ambition in implementing greenhouse gas (GHG) emissions reductions.

For each time period, we calculated an average national monthly representative maximum, mean and minimum temperature. The monthly values for each model and scenario were combined into one average value based on the arithmetic mean of all monthly temperatures in each model-scenario pairing, for the 16 models and four scenarios.

Monthly mean, maximum and minimum temperatures are used to calculate the equivalent WBGT. While there are various approaches to calculate the WBGT, we follow that used in Kjellstrom et al. (2014), where WBGT is calculated from air temperature and relative humidity to obtain 'indoor' or 'outdoor, in shade' WBGT values. The equivalent 'outdoor, in direct sunshine' levels are obtained by adding three



degrees to the indoor/in shade WBGT levels during daylight hours to reflect the additional heat stress caused by exposure to additional solar radiance.

Mean, maximum and minimum WBGT levels are combined into hourly WBGT profiles. Following Kjellstrom, Lemke, Otto, Hyatt, & Dear (2014) we define daily temperature profiles for each country and each time period. In the absence of actual data on the distribution of temperatures across the day in each country, we adopt a similar approach the Kjellstrom et al. method of assigning a daily temperature profile based on the minimum, average, and maximum temperatures for which we have data.

We use the WBGT ranges to fit a daily temperature profile for each of the 12 monthly representative days, using the profile shown inFigure 28. While we fit a generic temperature profile across all months and countries, the model interface is designed such that this can easily be updated as more granular data becomes available.



Figure 28. Fitting a daily temperature profile using the WBGT min max and mean temperatures

Source: Vivid Economics

User defined inputs and assumptions

A number of user-defined inputs and assumptions are used in applying this production function. The technical assumptions we make are summarised in Table 16. These are necessary both to represent the production function in a simplified model format, and in some cases due to data limitations.





Table 16. We base user-defined inputs and assumptions on peer-reviewed literature

Input	Assumption
	Model of the national economy
A _{s,c} sectoral total factor productivity	Calibrated for each country based on current data on temperatures, sectoral employment and output, other parameters in the model
$K_{s,c,t}$ capital inputs per sector	Sectoral shares of the total capital stock are assumed to be constant over all time periods Overall future levels of total capital stock are projected based on historic data and observed growth rates over the ten years from 2004 to 2014
<i>L</i> _{s.c.t} labour inputs per sector	Sectoral shares of total employment are assumed to be constant over all time periods Future total employment is projected based on ILO projections
Θ_s , (1- Θ_s) intra-sectoral share of capital in the production function, sectoral share of labour in the production function	The intra-sectoral share of capital in the production function indicates how much capital is needed for each unit of labour for each sector, and is based on country-level parameter from GTAP, held constant over time
$a_{\kappa,s}$ sectoral productivity of capital	Assumed to be equal to 1 for all sectors, held constant over time for all countries
$\label{eq:rhos} \begin{split} \rho_s &= \frac{1}{(1-\gamma_s)} \\ \text{sectoral degree of elasticity of} \\ \text{substitution} \end{split}$	Identified from the GTAP database for the seven sectors in the model based on appropriate comparator sectors Elasticities of substitution within each sector are assumed to be the same across all countries as per (Arrow, Chenery, Minhas, & Solow, 1961)
	Model of effective labour supply
exposure to sunlight	All work conducted in the Agriculture and Construction sectors is carried out outdoors in direct sunlight All work in all other sectors conducted indoors
work intensity	Work done in the Agriculture and Construction sectors is 'high' intensity work Work in Manufacturing and Other industry sectors is 'moderate' intensity Work done in all other sectors is 'low' intensity
working hours	Working hours vary by sector and country based on expert input
	Daily temperature profiles
scenario and model run for climate modelling input data	For each country and time period, we take an arithmetic mean of the 16 models available and all four RCP scenarios
WBGT calculation method	We calculate WBGT using established physics formulae We assume outdoor, in direct sunlight WBGT values are equal to indoor WBGT values plus 3 degrees
WBGT daily profile	We assume simplified daily WBGT temperature profiles based on daily sunlight and air temperature profiles

Source: Vivid Economics



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: vivideconomics

Contact us:

Vivid Economics Limited 26-28 Ely Place London EC1N 6TD United Kingdom T: +44 (0)844 8000 254 E: enquiries@vivideconomics.com

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