ADAPTING INDUSTRY TO WITHSTAND RISING TEMPERATURES AND FUTURE HEATWAVES.

Institution of
MECHANICAL
ENGINEERS

Improving the world through engineering

“”

The impacts of a warmer world on industry will be complex and broad, including technical, economic and health related, and the implications of the findings of this report are applicable across the globe. Adapting industries to, and preparing them for, a warmer world will be essential for the future successful functioning of societies of all nations.

Dr Tim Fox CEng FIMechE

Authors

Dr Tim Fox CEng FIMechE
Dr Laura Kent

Case Studies

Dylan Clark, Ricardo Pelai and Dr Guy Felio
Canadian Climate Institute and Dr. Infrastructure

Dr Guy Felio P.Eng. IRP[Climate] F-CSCE F-IAM
Dr. Infrastructure

Taryn Green MEnvSc LEED AP
Joel Good M.A.Sc P.Eng.
RWDI

Richard Tiplady CEng FIMechE ACGI
Chair, IMechE Process Industries Division

Dr Catarina Marques FInstR
Member, IMechE Food and Drink Engineering Committee

Prof. Toby Peters and Dr Leyla Sayin
Centre for Sustainable Cooling, University of Birmingham

Contributors

Armel Castellan
Meteorological Service of Canada, Environment and Climate Change Canada

Debdatta Chakraborty
Indian Institute of Technology Bombay

Dr Lida Dimitriadou
Academy of Athens

For more information contact:

Engineering Policy Unit
Institution of Mechanical Engineers
policy@imeche.org

Published April 2023
Design: Karoshi

Contributors (Cont.)

Prof. John Dora CEng FICE FIEMA FRMetS FPWI
Climate Sense

Dr Kostas Douvis
Academy of Athens

Dr. Guy Felio P.Eng. IRP[Climate] F-CSCE F-IAM
Dr. Infrastructure

Ian Gibbard
Therco-Serck Ltd

Joel Good M.A.Sc P.Eng.
RWDI

Taryn Green MEnvSc LEED AP
RWDI

Philip Jarrett
Environment and Climate Change Canada

Carola Koenig CEng MIMechE MASME FHEA
Brunel University London

Jonathan Krzyzosiak CEng MIMechE
The Hazards Forum

Prof D. Parthasarathy
Indian Institute of Technology Bombay

Professor Toby Peters
Centre for Sustainable Cooling, University of Birmingham

Eric Laurentius Peterson PhD
University of Leeds

Prof Milind Rane PhD
Heat Pump Laboratory, Indian Institute of Technology Bombay

Dr Leyla Sayin
Centre for Sustainable Cooling, University of Birmingham

Ruth Shilston MEng CEng FIMechE
RWDI

Dafni E. Sifnioti, FRMetS CMET
EDF Energy R&D UK Centre

Dr Stavros Solomos
Academy of Athens

Theodora Stavraka
Academy of Athens

Richard Tiplady CEng FIMechE ACGI
Chair, IMechE Process Industries Division

Prof Christos Zerefos
Academy of Athens

Contents

Synopsis

The economies of developed and developing countries worldwide are underpinned by a range of industries that have the heating and cooling of liquids, gases and solid materials at their core. Such industries include the oil, gas and renewable biofuels sectors, chemical and petrochemical processing, industrial gases production, pharmaceuticals, food and drink processing, minerals processing and the production of metals and synthetic materials, amongst others, all of which are sensitive to the temperatures in which they operate. Consequently, as the world continues to get hotter due to human-induced global warming and climate change leads to higher seasonal ambient temperatures and more severe heat extremes, their productivity will be impacted, with implications for local, national and international economic well-being.

Industrial processes, assets, buildings and personnel will all be negatively affected by higher temperatures. Indeed, exposure to heat levels beyond those for which designers have allowed can lead to detrimental outcomes for productivity, through reductions in the efficiency and performance of equipment, plant, buildings and people, and in extreme cases the complete shutdown of operations. To avoid such outcomes, industrial organisations need to plan and implement climate change adaptation measures as well as build internal capacity for resilience to extreme heat events.

This report from the Institution of Mechanical Engineers considers the challenge of adapting industry to future climate change-induced, heat-related impacts. It explores the effects on industry and its workforce of increases in ambient temperatures and more frequent, severe, prolonged heatwaves[A] and how engineers should respond. Most importantly, it examines the urgent need for engineering-related standards and design codes to be based on expectations of future climate rather than past climate; adaptation solutions to be sustainable and result in net-zero greenhouse gas emissions; and strategies to be developed to make workplaces and work practices comfortable and safe.

The impacts of a warmer world on industry will be complex and broad, including technical, economic and health related, and the implications of the findings of this report are applicable across the globe. Adapting industries to, and preparing them for, a warmer world will be essential for the future successful functioning of societies of all nations. It is vital that their integrity and productivity is maintained in a future environment characterised by an overall increase in ambient temperatures and intense heat events. To assist industry, governments, the engineering profession and academia to collaboratively prepare for this challenge, the report concludes with a number of key recommendations for action.

Introduction

The atmosphere, oceans and land of planet Earth are warming, and it is unequivocal that humans have contributed to this reality through the emission of greenhouse gases, deforestation and a myriad other activities. Indeed, atmospheric global mean temperature is now 1.2°C above pre-industrial levels[1] and, consequently, in many regions of the world summers are getting hotter and winters are becoming warmer, leading to significant impacts on weather, climate and other earth system processes. There have been increases in the intensity and frequency of heatwaves, prolonged droughts and wildfires and the water cycle has intensified with more evaporation and precipitation, intensifying both dry and wet events and seasons. The cryosphere is in retreat, including the glaciers, Arctic sea ice, spring snow cover and land-based ice sheets. The global mean sea level has been rising since the beginning of the 20th century, and the rate is accelerating[2,3].

With the greenhouse gas emissions reduction commitments and associated policies currently pledged by governments around the world, it is anticipated that global warming will continue at pace in the coming decades and the 1.5°C target of the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement will not be achieved**[B]**[4]. Indeed, future climate projections are in almost universal agreement that global mean temperature will rise above this target no later than the early 2030s, regardless of which emissions scenario is now followed, including one in which emissions peak and then reduce to achieve net-zero**[C]**[7,8]. The level to which it would eventually return if emissions reach net-zero is uncertain.

In response to a projected increase of such magnitude, it is crucial that humanity begins to prepare for the future through the adaptation of domestic life, public services, businesses and industry to climates with higher ambient temperatures and more frequent, severe, prolonged heatwaves. This will entail changes to the design of buildings, infrastructure and other physical assets and systems, both with regard to those that already exist and those that are yet to be built or manufactured, as well as the work, educational, leisure and other activities that humans undertake. Without such change, economic productivity will be reduced, learning will be impaired, human well-being will be degraded and, ultimately, mortality will increase[9].

From an engineering perspective, real change in the ambient temperature has occurred over the design life of existing infrastructure, industrial assets and buildings, many of which were built to withstand a cooler world. As temperatures continue to rise, there are concerns over decreased asset and process efficiencies, the impact on the health of workers and the resulting impact on economic productivity.

Helping society adapt to future heat impacts presents the engineering profession with significant challenges. Not least of these is that of designing for an uncertain future climate and ensuring that adaptation solutions fully integrate greenhouse gas reductions aligned with a net-zero outcome, as well as wider principles of sustainability. How engineers meet the challenge of adapting to increased temperatures will have important ramifications, not only for future climates, but also for the wider environment and a sustainable human future more broadly.

This report, researched and prepared by the Process Industries Division of IMechE in collaboration with sister Divisions and Groups, as well as members of allied engineering institutions and external subject matter experts from across the world, explores the impact of heat on the industrial workforce and the assets and buildings they use. It considers how hot the world may become, examines the effects of heat on people's health and their ability to work safely and productively, and identifies adaptation strategies to overcome the resulting workplace challenges. At the core of the study is an engineering-based review of the potential impact of increased ambient temperatures and more frequent, intense and prolonged heatwaves on industrial buildings and assets, such as equipment and entire plant. It presents the engineering challenges that designers, operators and owners face in adapting to these impacts and includes detailed consideration of an appropriate response by engineers to the need for updated standards and design codes; sustainable cooling technologies and processes; adaptation strategies to deal with uncertainty; and the education, training and skills development of the profession.

The industrial focus of the report is on a broad range of process industries in which the application of heat and control of temperature is fundamental to their outputs and economic productivity. Such industries include those supporting the clean energy and environmentally friendly materials revolution, such as biofuels production from waste and plastic replacement products; those that traditionally underpin the economic growth of developed and developing nations and are in transition to decarbonisation, such as oil and gas, mining and materials, chemicals and petrochemicals; and those that contribute to society's health and well-being, such as food and drink processing, sewage and wastewater treatment, pharmaceuticals and the production of medical oxygen.

The world is getting hotter

The emission of greenhouse gases (GHGs) from human activity are unequivocally making the world hotter[7]. As a result, the global mean temperature of the atmosphere is now approximately 1.2°C above its pre-industrial level[1] and while this increase may not seem significant, it is already causing climates to change, presenting humanity with substantial challenges[10].

GHGs absorb infrared radiation from the sun in the form of heat. Since the last glacial period (occurring between 115,000 and 11,500 years ago) of the Quaternary glaciation, commonly known as the Ice Age, the concentration of GHGs in the atmosphere has remained relatively constant, with their sources and sinks maintaining equilibrium[D]. This has resulted in a period of climatic stability in the current Holocene (interglacial) period, during which time modern civilisation has been able to emerge. However, since the industrial revolution began in the mid-18th century, humanity has significantly increased the burning of fossil fuels and the associated emissions of GHGs. In parallel, human activity has reduced the availability of sinks through changes in land use, such as deforestation and peat and wetland destruction. This has led to an imbalance in the previous state of equilibrium.

These extra anthropogenic (human) emissions have slowly overwhelmed the remaining natural sinks, resulting in a steady increase in the atmospheric concentrations of GHGs[11]. This results in an effect much like a gradually thickening blanket around the planet, meaning that increasing amounts of heat are captured in the atmosphere, slowly raising its temperature.

The increase in temperature over time will depend on the GHG concentrations reached within the atmosphere and in turn drive further changes in the climate system, which are expected to become more severe for humans and other natural living systems as levels rise[10]. Until a steady state of net-zero emissions is reached, GHG concentrations will continue to increase and so will the global mean temperature.

'Unequivocal'

Unequivocal is the word used by the Intergovernmental Panel on Climate Change (IPCC) to describe humanity's influence on the warming of the atmosphere, ocean and land[7]. Their message could not be clearer – the planet is already hotter.

"It is unequivocal that human influence has warmed the atmosphere, ocean and land"[7].

"The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years"[10].

However, it should be noted that even if emissions were reduced to a point where net-zero was achieved tomorrow, the climate would continue to change until all remaining effects had propagated throughout the totality of the climate system[12]. How high the global mean atmospheric temperature will ultimately rise is related to future emission rates that are entirely dependent on the activities of humanity and thus the actions and behaviours of people throughout society.

In terms of the heat-related effects that will impact on humans and natural systems, these will be discerned in two ways. Firstly, there will be a shift to warmer seasonal ambient temperatures throughout the year[13], as for example in the UK, which is projected to have hotter, dryer summers with warmer wetter winters[14] and where 2022 was the warmest year on record, exceeding the previous record set in 2014[15]. Secondly, there will be an increase in the frequency, duration and severity of extreme heat events, such as heatwaves[10].

Extreme event attribution studies explore the 'human fingerprint' on extreme weather, linking the tangible experience of weather with climate change[16,17]. In a recent analysis of 504 extreme weather events and trends, 71% were found to be made more likely or more severe by human-caused climate change. Of the 152 extreme heat events analysed by scientists so far, 93% found climate change made the event or trend more likely or more severe. It is almost certain that the number of hot days and hot nights will continue to increase over most land areas in terms of length, frequency and intensity[E][10].

In recent years, temperatures around the globe have reached new record-breaking highs. Greece, for example, faced an unprecedented heatwave in July and August of 2021 where temperatures reached 46.3ºC and were responsible for catastrophic wildfires[18]. In the same year, multiple cities in the US states of Oregon and Washington, along with the western provinces of Canada, recorded temperatures far above 40°C, including a new all-time Canadian temperature record of 49.6ºC in the village of Lytton, British Columbia, surpassing the previous 1937 record by 4.6ºC[19]. More recently, in 2022, temperatures in the UK reached 40.3ºC during the driest July in England since 1935, breaking the previous record of 38.7ºC[20].

China experienced an extreme heatwave in 2022 which could be amongst the worst recorded since meteorological records began. Temperatures of more than 40ºC were experienced for 70 days in a row, affecting more than 900 million people across the country[21]. This event resulted in drought and forest fires, affecting agricultural production and water resources. Parts of the Yangtze River dried up and the loss of water flow to China's hydropower system sparked serious concerns in Sichuan, where more than 80% of its energy needs are met using that technology. Factories were ordered by the government to shut down for six days because they couldn't meet the power demands[22].

Heatwaves can be intensified in a phenomenon known as a 'heat dome' event, which results from a sinking air mass and compressional heating. In this event, a persistent region of high pressure with low wind speeds traps heat over an area, often increasing the humidity. It can stretch over large areas of land, resulting in stagnant hot air and impacting the health of people, crops and animals[23]. Heat domes can last multiple weeks, and it is such a feature that was responsible for the extreme temperatures seen in the US and Canada in early summer 2021 (see Case Study on page 17–18).

These extreme heat events lead to a spike in emergency calls and hospitalisation and are linked to an increase in the number of deaths recorded[24]. Beyond the human impact, infrastructure can struggle to cope with the resulting high temperatures, which are often in excess of those for which they were designed. For example, during the extreme heat of July 2022, Luton Airport in the UK saw temporary disruption when a patch repair to the runway became so hot that it de-bonded and began to lift, halting further landings and take offs by aircraft[25]. Train tracks can buckle in the heat, and in the past 40 years, kinks in steel tracks caused by the sun have caused over 2100 train derailments in the United States[26]. Industrial buildings and assets, such as equipment and plant, are also at risk, as illustrated in France when soaring temperatures threatened to shut down nuclear power plants[27]. Further, heat impacts are magnified in urban areas, both industrial and residential, and these are set to increase as estimates predict that around 70% of the world population will live and work in cities and urban conurbations by 2050[28].

There is a public health and economic impact associated with rising temperatures and extreme heat events that governments and industries must prepare for through adaptation and the building of capacity for resilience. A society that is failing to plan for extreme heat is planning to fail.

Heat impacts on people and their places of work

Heatwaves lead to serious effects on human health and are an emerging public health issue. Today, they are the most prominent reason for weather-related human mortality, accountable for more deaths on an annual basis than floods, hurricanes, tornadoes, lightning and earthquakes combined[29]. Exposure of vulnerable groups (ie, children, pregnant women, the elderly, people with pre-existing health problems, people with chronic mental disorders, etc.) increases their susceptibility to higher temperatures, placing heatwaves in the centre of public health challenges in the 21st century. Further, in the context of economic productivity, the International Labour Organisation (ILO) projects that the economic losses due to heat stress[F] at work will be US$2,400 billion in 2030, predominantly impacting lower-middle and low-income countries[30]. This is equivalent to 80 million full-time jobs. The challenges of heat stress are also pronounced in piece-work based and informal employment, where workers often operate in sub-optimal conditions and do not receive adequate medical care, paid leave and sickness benefits during the period of incapacity for work. It is important that society correctly addresses heat and the impacts on productivity as well as health[31].

Heat is experienced differently across occupations and employment sectors. Rising temperatures pose serious health risks to workers toiling outdoors in the sun for long hours. Those working indoors can also be impacted by increased heat in the absence of effective controls on ambient temperatures at the workplace. Occupations which involve greater physical exertion, like heavy lifting and manual labour, are likely to be more affected, since individuals become exhausted faster and metabolize heat less effectively under strain[32]. Jobs that necessitate workers to wear heavy clothing and personal protective equipment (PPE) are also more likely to be affected by heat stress[33].

To understand heat impacts in the workplace it is important to establish what is meant by thermal comfort. In this regard, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines thermal comfort as "the condition of the mind in which satisfaction is expressed with the thermal environment"[34]. There are six basic contributing factors to thermal comfort, four of which relate to environmental conditions and two to personal factors (**Table 1**)[35].

Table 1: The six basic contributing factors to thermal comfort[36]

Air Temperature	The temperature of the air surrounding the body, usually given in degrees Celsius.
Radiant Temperature	Thermal radiation is the heat which radiates from a warm object. This has a greater influence on how heat is lost to, or gained from, the environment than the air temperature.
Air Velocity	Describes the speed of air movement which may help to cool if the air is cooler than the environment. For example, still air in an indoor environment that is artificially heated feels stuffy.
Humidity	Humidity is the amount of water vapour in the air. The relative humidity is the ratio of the actual amount of water vapour in the air and the maximum amount of water vapour that the air can hold at a given temperature. There is little impact on human comfort between 40% and 70%. High humidity environments have a lot of water vapour in the air, preventing the evaporation of sweat from the skin, which is the main method for the body to reduce heat.
Clothing Insulation	Clothing provides an insulating effect. Wearing too much clothing or PPE may cause heat stress even if the environment itself is not hot. Many industries and companies are limited in the ability to change PPE to ensure safety is maintained.
Metabolic Heat	The more physical work a person does, the more heat they produce which needs to be lost to prevent overheating. This can be affected by a person's size, weight, age, fitness, sex, natural metabolism and medical conditions.

Thermal comfort is very important in a workplace and if it is not achieved, morale, productivity, health and safety will all likely deteriorate. Poor thermal comfort means colleagues are more likely to behave unsafely and make poor decisions. For example, in hot environments workers may be tempted not to wear personal protective equipment properly, leading to greater safety risks. Heat may also affect a worker's ability to concentrate on a given task through decreased cognitive function, increasing the chances of errors and accidents, thereby reducing productivity. Ultimately, workers may take action and strike, reducing productivity to zero, as was the case in summer 2022 in automotive manufacturing facilities in Italy, where employees downed tools because indoor temperatures were unacceptable and cooling systems were unable to operate due to an energy crisis. Those working in a comfortable environment will be relaxed and able to concentrate on tasks. It will positively impact morale and make a workplace more appealing, leading to greater staff satisfaction and retention and achieving better productivity levels.

The acceptable temperature of an indoor workplace in the UK is covered by guidance from the Health and Safety Executive (HSE) in a document known as the Workplace (Health, Safety and Welfare) Regulations 1992, which places a legal obligation on an employer to provide a working environment at a reasonable temperature[36]. The Approved Code of Practice suggests the minimum temperature of a workplace should normally be at least 16ºC, or at least 13ºC where the work involves rigorous physical effort. It is difficult to set a meaningful upper temperature though, due to variations between industries in conditions and work effort. The HSE also have a 'Thermal Comfort Checklist' to help identify if there is a risk of thermal discomfort, and an environment is said to be reasonable when at least 80% of the occupants are comfortable.

The standards most commonly used to predict thermal comfort, ASHRAE 55-2016 and ISO 7730, are based on the Fanger model[34,37]. The Fanger model calculates the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) of comfort for a group based on air temperature, mean radiant temperature, relative humidity, metabolic rate and clothing insulation. This can be simulated during the design process.[G] The PMV model adopts a seven-point scale from hot, +3, to cold,-3 (**Figure 1**).

Figure 1: Fanger model based thermal comfort scale[38]

However, this model does attract some criticism, as it is based on data collected from males wearing suits in an office environment, which, for example, will not necessarily be relevant to workers on an industrial site wearing several PPE layers and carrying out differing levels of physical exertion. Additionally, the comfort temperature amongst females is higher than that of males. Importantly, the Fanger model does not allow for physical measurements to be made in situ making it difficult to monitor and implement reactive actions in high heat stress situations.

Alternatively, a wet bulb globe temperature (WBGT) can be used, and this approach is particularly common in sports. For example, FIFA guidelines allow for cooling breaks in the 25th and 70th minutes of football matches if the WBGT exceeds 32ºC, or 28ºC for the under-20s teams[39]. Beyond sports, military agencies and the US Occupational Safety and Hazard Administration (OHSA) have guidelines based on the use of the WBGT[40].

The WBGT is a measure of heat stress which takes into account the temperature, humidity, wind speed and solar radiation. It helps to explain why high temperatures on holiday in shorts with a cold drink are more bearable in climatically dry countries than when the same temperature is reached in the UK, where the humidity is higher. Importantly, WBGT can be both simulated and physically measured. By 2080, there may be 150–750 million person-days of exposure to wet bulb globe temperatures (the lowest temperature to which the body can be cooled through evaporation at the local atmospheric pressure) above those seen in today's most severe heatwaves[41]. The higher the WBGT, the more stressed the body becomes, and at 35°C a limit is reached where continued exposure without alternative cooling will result in human mortality (there is some recent research that found this limit could in fact be lower).

Through mutual dialogue supported by sensitive policies and regulations, employers and workers can design strategies for dealing with heat stress that are tailored to the specific needs of the different categories of workers and contingencies of their workplace[30]. The focus should include the monitoring and modelling of the WBGT.

BP Safety Manual for US Pipelines and Logistics

In their Safety Manual for the US Pipelines and Logistics teams, BP has a policy in place to provide the necessary information to recognise, assess and control heat stress in the workplace[42]. Supervisors are responsible for recognising the hazards of working in hot environments, mitigating the risk of heat stress and enforcing engineering controls and appropriate work practices, and watching for signs of heat stress. Additionally, employees are responsible for taking basic precautions to prevent heat stress.

To prevent heat stress, administrative cautions are suggested, including:

- Hydration – access to potable drinking water and, where the supply of water is not plumbed, at least one gallon of water per employee per shift is provided. The frequent drinking of water is encouraged.
- Cooling mechanisms – access to shade is permitted at all times, and in lieu of this, cooling measures may be provided providing they are at least as effective as shade.
- Administrative controls – consideration of modified work schedules, extra breaks, buddy systems and a work/rest cycle.
- Heat Index Values – chart to demonstrate how hot it feels when relative humidity is factored with actual air temperature. These values then dictate the recommended work/rest schedule (**Table 2**).

A person wearing protective clothing, such as FRC, and performing work in hot and humid conditions may be at risk of heat stress for multiple reasons. For example, sweat evaporation can be restricted by the clothing required to safely do the job or because the humidity is too high. As the core body temperature rises, the body reacts by creating more sweat, increasing the risk of dehydration.

Table 2: Heat Index Values and associated actions[42].
(FRC refers to Flame Resistant Clothing, which is more insulating than non-FRC clothing, and the times represent the recommended work/rest schedule.)

Heat Index Values (ºF)	**Inside vessels, with FRC**	**Outdoors in sun, with FRC**	**Outdoors in sun, without FRC**
90–104 ºF	45 min. / 15 min.	60 min. / 15 min.	90 min. / 15 min.
105–130 ºF	30 min. / 30 min.	45 min. / 15 min.	60 min. / 15 min.
130 ºF and higher	Discontinue work. Contact HSE for further evaluation	Discontinue work. Contact HSE for further evaluation	Discontinue work. Contact HSE for further evaluation

The impact felt from increased heat, seasonal changes and extreme heat events will particularly effect industries which currently operate at a high temperature, such as power plants, mines and foundries. Excessive heat at work is an occupational health risk. It restricts physical functions and capabilities and impacts on work capacity and productivity. During periods of intense heat, performing even basic tasks becomes arduous as fatigue sets in. The worker slows down, takes more frequent and prolonged breaks or reduces their working hours, which adversely affects their productivity, economic output and, particularly if employed in the informal economy or piece-work (as is often the case in low-income and developing countries), family income[43]. A worker functioning at moderate work intensity loses 50% of their labouring capacity at 33–34ºC[30]. Heat beyond a 38ºC threshold can cause heat exhaustion leading to fatigue, weakness, dizziness, headaches, nausea, vomiting, muscle cramps and sweating[45]. Temperatures above 40ºC can lead to heatstroke, which sometimes has fatal outcomes[44]. A recent study attributes anthropogenic climate change to 37% of the warm-season heat-related deaths across 43 countries between 1991 and 2018 and that this increased mortality is happening on every continent[46].

The prevention of dehydration is a key action to help avoid heat stress occurring as a result of worker exposure to high temperatures. In this regard, HSE guidance states that cool water in the workplace should be available and workers encouraged to drink it frequently in small amounts before, during (where possible) and after working. The HSE's Workplace (Health, Safety and Welfare) Regulations 1992 state that "an adequate supply of wholesome drinking water shall be provided for all persons at work in the workplace"[47].

Direct exposure to extreme weather events can lead to loss of life and breakdowns in physical health. However, there are also enduring impacts on the mental health of those who are exposed to them, including depression, anxiety, post-traumatic stress, sleep deprivation and suicide[48]. The physical impacts on changes to people's local environments will also increase the risks of mental illnesses, decreasing wellbeing and therefore imposing significant costs to individuals and governments[49].

Administrative measures, such as the enforcement of occupational health and safety standards in all workplaces, monitoring of local weather conditions and workplace temperature, improved early warning systems and effective communication of heat alerts to workers, can prevent heat-related negative health outcomes[43]. Similarly, raised public awareness about the harmful effects of heatwaves on human health and guidance for the safety of vulnerable groups, such as older people, children and pregnant women, can also help. More specifically, the scheduling of rests at regular intervals during work hours, promoting proper acclimatisation measures, and observing the health status of workers, along with ensuring the provision of water and electrolytes and access to emergency medical services, can all enhance workers' adaptive capacity to rising temperatures[50]. Happier and healthier workers will perform their work safely and productively.

Case Study

Lessons from the 2021 Heat Dome event

A heat alarm was felt globally when one of the most extreme high temperature events in recent years impacted North America in June 2021, significantly breaking record temperatures and setting concerns that the magnitude of extreme weather events is increasing faster than expected. The subsequent heatwaves experienced in Europe and China in the summer of 2022 illustrate how these unprecedented and devastating climate change-related events are impacting the health and livelihoods of millions. What can be learnt from the 2021 Heat Dome event over North America to better prepare people and industries for future events?

In June 2021, a high-pressure weather system trapping heat, known as a heat dome (see description on page 9), built up over British Columbia in Canada and the Northwestern Pacific of the United States. The heat dome broke temperature records in multiple cities and set a new all-time Canadian temperature high of 49.6ºC in the village of Lytton, significantly exceeding the country's previous national record by 4.6ºC[24]. The event is thought to have been caused by a combination of high atmospheric pressure and dry conditions. The months before the event had been drier than usual, leading to drought conditions that caused a feedback loop whereby the sun's energy was converted into heat rather than evaporating water in the soil, warming the near-surface atmosphere. Although an unprecedented event in 2021, a recent study has shown that by 2080 similar heatwaves have a 1 in 6 chance of happening yearly in western North America.

Between June 25th and July 1st 2021, the heatwave was responsible for 619 deaths along the west coast, with at least 595 of these occurring in British Columbia. Hundreds more were hospitalised, putting a strain on health care and emergency response systems. Devastating wildfires swept across Canada and the US. In Lytton nearly every house in the village was destroyed. Those that were spared were cut off from electricity, sewer and water services. The post office, ambulance station, health centre, village office and hotel were burnt to the ground. There was damage to the railway and highway infrastructure, some of which is still out of action. Figures from Catastrophe Indices and Quantification Inc show that Can$102 million in insured damage had occurred[51].

In British Columbia, 79% of those who died were 65 or older. Those with pre-existing health illnesses, such as diabetes and asthma, were also at an increased risk. The risk was almost threefold for those with schizophrenia. These are vital groups to whom resources and support must be provided during heat events. The risk of death rose by 188% in both materially and socially deprived neighbourhoods. Access to cooling reduces health risks significantly, and for those at risk, it should be considered as a 'right', or an essential medical provision. Coverage of a 5% tree canopy was associated with a risk reduction. Tree canopies and access to green spaces matter and significantly impact all types of neighbourhoods.

In the wake of the 2021 heat dome event, British Columbia's authorities have published an 'Extreme Heat Preparedness Guide', similar to those produced for earthquake guidance, to help people evaluate if they can safely stay at home or not during these events. Officials have adopted the Sendai Framework for Disaster Risk Reduction, implementing programs that prevent and reduce hazard exposure and vulnerability to disaster and increase the preparedness for response and recovery, strengthening resilience. Recommendations include the installation of heat pumps for cooling provision in all subsidised buildings and low-income apartments and that building codes should require higher standards of heatwave readiness.

While significant work is underway across British Columbia to better understand and reduce the impacts of extreme heat to human health, there is a lack of information on the economic impacts of the heatwave, including its tangible and intangible costs to governments, businesses, the economy and overall wellbeing. As climate change continues to increase the frequency and severity of extreme heatwaves, understanding and quantifying these impacts is critical to informing and mobilizing effective adaptation and response actions. In this regard, the Canadian Climate Institute (Canada's leading climate change policy research organisation) is assessing the economic impacts of the 2021 Heat Dome and analysing the benefit of key evidence-based adaptations. This analysis will provide information to support the Government of British Columbia and other governments across Canada in developing policies and actions that build resilience to extreme heat and other climate change risks. The work is being funded by the British Columbia Climate Action Secretariat, but the Canadian Climate Institute will conduct the project independently.

The study has three phases:

- **Phase I:** Interviews and a literature review to determine which impacts of the 2021 heatwave should be prioritised in Phase II and Phase III.
- **Phase II:** Interviews with key informants (building off Phase I).
- **Phase III:** Economic analysis of the costs of the 2021 heatwave priority impacts.

Quantifying these impacts is crucial in informing policy, and the outcomes of the work will be published in 2023.

Overheating of industrial assets

The industrial assets focus of this report is on sectors that use temperature-related processes on materials either in liquid, gaseous, solid or multi-phase form, to provide feedstocks or finished products which underpin the economic growth and well-being of developed and developing nations worldwide. Outputs of these industries, known as the process industries, include mined minerals, metals, gas and oil products such as plastics, aviation fuel, diesel and petrol, biofuels, alternative sustainable materials, pharmaceuticals, fertilisers, food and drink, potable water, treated sewage and wastewater, medical oxygen and industrial gases, amongst many others.

The economic and societal contribution of the process industries is significant. Indeed, the Chemical Industries Association estimate that the pharmaceutical and chemical industries alone in the UK "directly employs over 150,000 highly skilled people who on average earn 35% more than other manufacturing industries and 54% more than the average worker in the economy" and "adds almost £25 billion of value to the economy, on estimated sales of around £66.7 billion"[52].

The application of heat and control of temperature is fundamental to these industries which use processes requiring substantial thermal input, such as distillation, evaporation, smelting, sterilisation, pasteurisation and baking, or those that are exothermic (heat generating) and therefore require significant thermal extraction to control the chemical reaction taking place. Other cooling requirements include, for example, to condense distillation fractions, to solidify products, and to remove the heat of compression for high-pressure gases. Climate change-induced increases in ambient temperatures and heat extremes are therefore critical to the performance of these processes and have the potential to impact significantly on sector productivity at local, national and global scales.

Cooling Systems used in Process Industry Assets

The cooling of gases, liquids and two-phase flows in the process industries normally takes place in heat exchangers where the heat is transferred from the process fluid to a cooling medium. The cooling mediums can include:

- Water – surplus heat energy is withdrawn from the process fluid typically in shell and tube or plate heat exchangers by transfer to a cooling water circuit. The surplus heat is then expelled into the atmosphere via wet cooling towers or directly to river water or sea water.
- Air – surplus heat energy is expelled directly to the atmosphere by forcing large volumes of air over large banks of finned tubes containing the process fluid or cooling water circuit.
- Refrigeration – surplus heat energy is withdrawn from the fluid in heat exchangers by transfer to cold refrigerant fluids. The surplus heat is then often expelled into the atmosphere.
- Other process fluids – surplus heat energy is transferred to other, colder process streams in a range of heat exchangers; for example, cryogenic fluids or gases in the plate-fin units used for air separation processes in the industrial gases sector to deliver nitrogen, oxygen, argon, etc.

The selection of appropriate cooling processes and equipment in an industrial asset is complex and must consider design factors, such as the energy transfer required, the flow rates of the process and coolant fluids, the incoming temperatures of the fluids and the required temperature reduction.

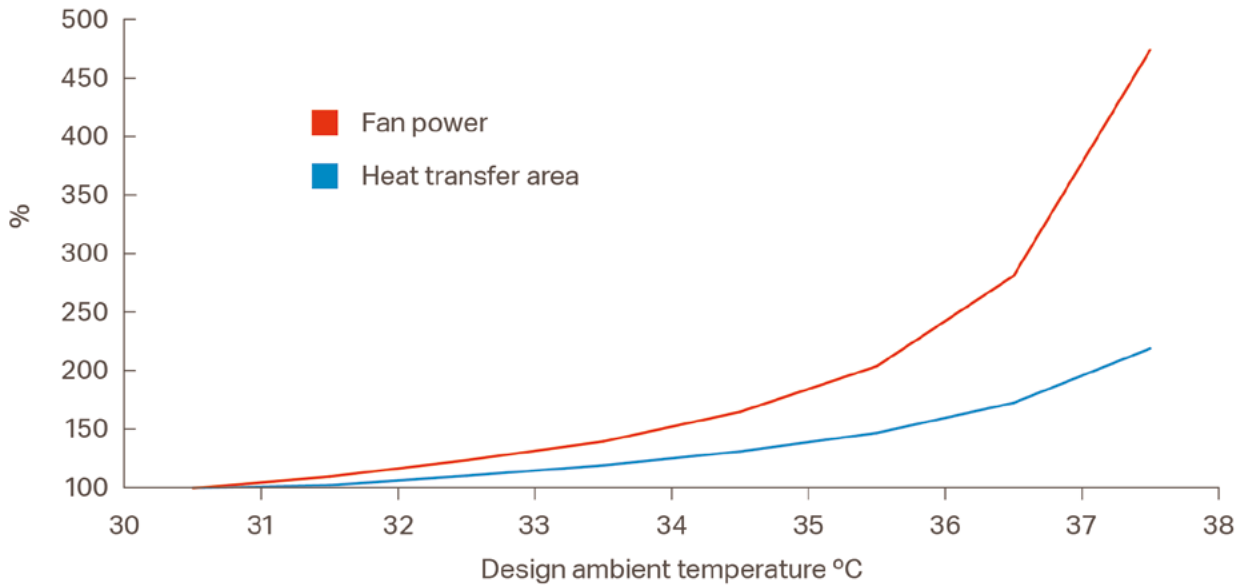
Inter-process fluid heat transfers are generally independent of ambient temperature, as they are typically at elevated temperatures significantly higher than the ambient temperature (apart from in the case of cryogenic fluids). Sea-water-cooled systems are also generally independent of short-term local air temperature fluctuations, as the thermal capacity of the sea dampens the effect of air temperature changes. In this regard, water intakes are normally located at depth and significantly distant from the shore, such that surface and shore heating effects are minimised. However, prolonged climate change-induced heating of inshore waters can lead to issues with the performance of sea-water-cooled systems, as, for example, seen in the nuclear energy sector where coastal-based power stations can be impacted by prolonged heatwaves[53].

River and estuary water temperatures are, however, influenced by local changes in ambient temperature as well as extreme heat events and can impact significantly on the performance of systems based on the use of coolant abstracted from such sources[54]. Wet cooling tower systems become less effective as temperatures and humidity increase.

However, most critical to the sector are the impacts on air cooling and refrigerant cooling systems, both of which become less effective as air temperatures increase and ultimately become ineffective when the ambient temperature approaches the process fluid temperature. The degradation of air-cooled heat exchanger (ACHE) performance can have a significant impact on the economic productivity, and ultimately the commercial business model, of an industrial asset.

ACHE units are used in many industrial assets to cool gas and liquid flows and are essentially banks of finned tubes (finning creates additional surface area) through which the process fluid passes while fans driven by electric motors force, or draw, air over the tubes. Heat is transferred from the process fluid to the air, essentially through a mechanism similar to that in a car radiator, just on a much larger scale. As the ambient air temperature increases, the differential temperature between the process fluid and the air reduces, and as such the total surface area of finned tube and the air flow required must both increase. To increase the air flow, the size and / or number of fans and motors required must also be increased. **Figure 2** shows the effect of increased ambient air temperature on both the installed surface area and the installed motor power required.

Figure 2: Normalised effect of ambient temperature rise on ACHE requirements (100% is base case, 30°C design ambient)[55]



The capital cost of a system is directly linked to the heat transfer area, so for a 5°C increase in ambient temperature above 30°C, the capital cost for the equipment will increase by 50%. The fan power, and hence electricity consumed, increases much more rapidly, such that it doubles with a 5°C ambient temperature rise, leading to increased operational costs.

As well as leading to degraded economic performance of the asset, the greenhouse gas emissions of the system also increase, therefore impacting on national strategies for climate change mitigation through emissions reduction. For example, in an oil refinery with air cooler installed motor capacity of 2MW, the summer CO_2 emissions would be over 200Te each month (based upon best UK carbon intensity for electrical grid), but a 5°C increase in design air temperature to 35°C would result in CO_2 emissions doubling to 400Te per month.

Extreme Heat and Net-Zero Technology Performance

Net-zero investment decisions must address the threat from extreme heat events, the impact of which will vary between technologies.

Carbon capture technologies vary, but all require significant energy input and subsequent cooling. Capturing and transporting CO_2 as a compressed gas or a liquid requires significant cooling capacity to support the compression and liquification of the CO_2.

Where the carbon capture is independent of the emitting process, such as in direct air carbon capture (DACC), the plant can be slowed down or stopped during periods of extreme temperatures. Indeed, most DACC systems will be designed for intermittent operations due to their reliance on available zero-carbon electricity. Recent extreme heat events have been aligned with high network electrical demand and hence high costs. To mitigate this problem in the future, the design and investment model for DACC units can be based upon ceasing operations during extreme temperature events.

When the carbon capture is integral with the carbon-emitting process, such as hydrogen manufacture from natural gas, and the hydrogen production is continuous to support industrial processes, the carbon capture process will also need to be continuous. As such, the designer of the capture technology must consider the extreme temperatures that could be experienced over the operating life of the process plants and adapt the design to accommodate as required.

Hydrogen manufacture, either via catalytic processing of natural gas or via electrolysis of water, requires significant cooling capacity to bring the hydrogen temperature to an acceptable level for compression and transport.

Process industry assets have for many decades operated successfully at extreme temperatures. For example, oil and gas extraction and refining takes place in the Middle East at temperatures of more than +50°C as well as in Siberia at -50°C. However, the design and construction of the plants differ considerably between the two locations, as do the business models upon which the asset's commercial performance is predicated.

For example, Northern European oil refineries may be designed for temperatures between -15°C and +30°C, the -15°C being specified to address issues of low-temperature metal toughness and the upper +30°C value used to design air-cooled heat exchangers. A similar refinery in the Middle East may be designed for 10°C to 55°C and, as such, low-temperature toughness issues will not be of concern. The design of cooling systems will, however, be significantly larger, need more energy to operate, and may require higher-cost cooling equipment, such as water-fed heat exchangers to replace what would be air-cooled versions in Europe. So, in each case the 45°C design temperature range results in quite different facilities with different capital and operating cost profiles, commercial business models and physical footprints. Simply transferring designs from the Middle East to northern latitude countries is not therefore a valid adaptation response to climate-induced ambient temperature rises and increases in the intensity and frequency of extreme heat events. Differences in energy, labour, material and equipment costs, as well as in land use pressures and decarbonisation aspirations, mean that such an approach would potentially be both unacceptable and commercially unviable.

The summer 2021 heatwave that affected the North-western Pacific of the USA and Western Canada (known as the 2021 Heat Dome and discussed earlier in this report) exposed industrial plants and facilities to temperatures exceeding 40°C, while many inland Canadian facilities frequently experience -40°C temperatures in the winter. To design, build, operate and maintain process plants reliably for an ambient temperature range of more than 80°C is an engineering challenge not experienced in many locations.

With climate change leading to more periods of extreme heat, the need to design and operate process industry assets at a wider range of temperatures will require this challenge to be addressed more widely.

Darren Gee, President & CEO of Peyto Exploration & Development Corp[56], a company involved in exploration for, and production of, unconventional natural gas in Alberta's Deep Basin, summarised the situation in his July 2021 Monthly Report[57] written just after the heatwave:

"The heatwave that ripped through Alberta and BC last week, as well as the US Pacific NW sent energy markets reeling – particularly natural gas and power prices. Low spring run off and low hydro levels meant less power generation and "heat-offs", the opposite of freeze-offs, reduced gas supplies right when the air conditioners were drawing max electrical load. Interestingly, natural gas receipts were hit particularly hard… as northern gas compressors struggled to operate in the 40+°C ambient temperatures. Most are not designed to run in that heat, much the same as Texas natural gas wells are not designed for sub-zero temperatures. We felt it at Peyto too, which impacted our June production. There were even days when significant gas was withdrawn from AECO storage to make up the shortfall, which means tighter supply for next winter when storage is critical"[57].

Continuous industries, such as oil refining, water treatment, sewage treatment, gas processing, and bulk chemical manufacturing are generally operated continuously 24 hours per day, 7 days per week, whereas fine chemicals, food production and pharmaceuticals may be operated intermittently or on a batch basis. Those with intermittent operations offer greater adaptability to extreme heat events as they can be shut down temporarily during periods of extreme heat, though commercial impacts may be severe due to the unpredictable timing and length of these events. However, industrial assets in sectors relying on continuous operations cannot respond with shutdowns. Wide-ranging adaptation is therefore required to ensure the continued performance of these industries that are critical to local, national and global scale economies.

Case Study

Extreme heat impacts on the Canadian mining sector

Asset-intensive mining operations in Canada experience harsh weather conditions, with prolonged frozen periods as well as periods of extreme heat, and climate change is leading to longer and more intense periods of high temperatures. The equipment and facilities are designed to operate over a wide range of temperatures, but these ranges will potentially not be sufficient to cope with future heat impacts.

For example, mining relies on conveyor systems to carry raw or processed materials around sites and these are particularly affected by significant variations of temperature and extreme heat events. Conveyor belts, usually rubber (neoprene) for mining operations, will soften and expand as temperature rises. When extreme temperatures are reached, the tensioning mechanism's ability to control tension will be exceeded, causing belts to jam and friction at drive rollers, potentially resulting in belt fires. As such, at extreme temperatures it can be necessary to shut down the mine operations. An hour of down time can cost a mining company around CAD$200,000.

Electrical and control equipment is not immune to extreme heat, particularly when the electronic components are housed in metal enclosures to protect them from physical damage and extreme cold. During extreme heat events, especially when exposed to radiant sun, the enclosure's internal temperature can exceed ambient temperatures. Such high temperatures can lead to loss of calibration for instrumentation and failures in electrical terminations due to thermal cycling.

Cooling requirements for process equipment increase as temperatures rise in the plant, adding load to the electrical systems which can themselves overheat and fail or cause fire hazards.

Prolonged episodes of extreme heat with associated drought will also impact the water source used in cooling the process equipment. This reduces the efficiency of the equipment, requires closer monitoring and adjustments and overall not only generates additional costs but also reduces production outputs and revenues.

Heating, Ventilation and Air Conditioning (HVAC) systems in on-site buildings are also affected by extreme temperatures or heatwaves. This will not only affect the people working in process buildings and offices if the cooling effectiveness of the systems is not sufficient, but can also impact areas where sensitive data (process, reporting) is collected and analysed.

Impacts of extreme heat on industrial buildings

In addition to industrial assets such as equipment and plant being subject to the impacts of extreme heat events, buildings located on industrial sites can also be significantly impacted, with resulting productivity and economic losses.

Extreme heat was once a rare occurrence in northern climates like that experienced by the UK. In such cases, climate-responsive building design has historically focused on addressing cold winter temperatures, through measures such as insulation, air tightness, and facilitating passive solar heating through the building façade. However, as climate change continues to impact weather patterns, the UK and other northern countries will experience more extreme temperatures and heatwaves. Peak temperatures exceeding 30°C for multiple days in a row, as seen in the summer of 2022, are no longer rarities in these regions and are anticipated to increase in frequency. In the UK, the duration of heatwaves has more than doubled, from 5 days historically to the current average of 13 days[58].

Extreme heat can have widespread and severe effects on buildings and their associated infrastructure. Buildings that were not designed for prolonged periods of high temperatures are often incapable of passively shedding heat and become susceptible to overheating, thermal discomfort and strain on mechanical systems. Industrial buildings are particularly susceptible due to their high internal loads and, in many cases, lack of ceilings and insulation. During the 2022 summer heatwave in the UK, Google and Oracle had issues with data centres overheating because the installed cooling infrastructure was insufficient to expel the additional heat load to the outside ambient environment and maintain the required internal temperature.

There are nearly 1.7 million non-domestic buildings in England and Wales. Factory spaces represent over 25% of that floor area[59], roughly 150 million square meters. Factories are also the most energy-intensive non-domestic building type, consuming 34% of total energy, with electrical consumption more than twice that of any other building use[59]. The high energy consumption is a result of high process loads (eg motors, drying/separation, high-temperature processes, low-temperature processes, etc).

With high internal heat gains, industrial spaces have inherently high cooling loads and, when combined with the fact that these building types are not typically designed with passive cooling measures in place, such as insulated lofts, overhanging shades and white painted roofs[60], this means that industrial buildings are very susceptible to overheating during heatwave events. Vulnerability, in the context of climate change, is considered the degree to which a system is susceptible to, or unable to cope with, the adverse effects of a climate hazard. In this case, the vulnerability of industrial buildings to extreme heat is a function of their sensitivity to heat and their adaptive capacity, or ability to adjust to and cope with climate hazards and impacts. Risk exposure is evaluated by considering both the likelihood (or probability) and consequence (or severity), of climate impacts. The nature of factories and industrial buildings is such that the likelihood of overheating occurring during a heatwave is increased and the consequences of building overheating can be significant. Industrial buildings are, in many cases, both vulnerable and at risk in the context of climate change induced heat impacts.

Similar to any building with occupants, thermal comfort and occupant health is a primary concern during overheating scenarios. As discussed earlier in the report, for workers who are potentially already working in a hot environment, an overheating workspace can potentially lead to heat stress, dehydration, heat exhaustion or heat stroke. As well as the physical dangers to employees, occupational heat stress also leads to decreased work efficiency, increased accidents and downtime, and increased health care costs and sick leave, all of which lead to decreased labour productivity and production, resulting in economic burden[61].

Overheating can also lead to damage to sensitive equipment or processes that require controlled setpoints (eg sensitive computers, refrigeration equipment, etc.) and can increase wear and tear on mechanical equipment. Similarly, excessive heat can limit the building system's ability to reject heat or maintain tight control on humidity levels. As continuity of operation is critical in the case of many industrial buildings, the consequence of system failure within could be severe, with impacts on the productivity and, ultimately, financial health of the businesses that occupy them.

At a larger scale, beyond the walls of the buildings and the industrial assets themselves, heatwaves can lead to potential local and regional power failures. For example, during the European heatwave of 2022, power production was curbed across the continent as natural gas-fired stations ran less efficiently, nuclear generation struggled to provide necessary cooling and drought threatened water levels relied upon for hydropower[62]. Recent extreme heat events have also highlighted the fragile nature of the electrical distribution network.

Where historically industrial buildings and process plants could count on the reliability of the electrical network, with backup systems to cover the very rare events, such as those associated with winter storms (when external power supplies are lost and island-mode operation is instigated), repeated and extended power loss events are becoming quite common during summer months. These outages are due to effects of high temperatures on overhead power lines and transformer stations, as well as, in some cases, simultaneously high network demand from air conditioning. Under-investment in power distribution infrastructure, combined with increased demand on the networks during period of extreme heat, means that industrial building and plant operators require adaptation plans to safely cope with multiple and extended power outages during periods of high temperature. Loss of power interrupting production of industrial processes could lead to significant economic losses.

Case Study

Improve Resilience of Industry Sector (IRIS) project (Italy)

The IRIS project[63] was funded by the European Commission's LIFE program and brought together partners from across industrial and manufacturing sectors in Italy. The project focused on improving climate resilience for industrial operations, particularly for small and medium enterprises which benefit from sharing skills and resources. The project's core actions included climate risk assessments and adaptation plans across a pilot suite of projects, as well as the development of a web portal aimed at sharing tools for climate risk self-assessments across industrial enterprises in Europe.

Three pilot locations were selected:

- the Bomporto industrial area is a 95 hectare site in the Province of Modena that includes over 80 enterprises from the manufacturing sector;
- the San Giovanni di Ostellato industrial area is a 120 hectare site in the Province of Ferrara that includes 30 manufacturing enterprises; and
- the Carlsberg Italia plant, including historic facilities that date back to 1876, in Induno Olona, Province of Varese.

Each pilot project included a climate risk assessment, development of a climate adaptation plan to address specific climate hazards, communication plan and exploration of funding opportunities. The climate risk assessment process included analysis of the climate context and events, definition of risks and evaluation of the probability and magnitude of occurrence. Specific considerations for the industrial and manufacturing sector included assessment of impacts to production facilities and machinery, supply chains, health and safety of personnel, financial stability and critical infrastructure.

Heatwaves and extreme heat were identified as a primary climate risk for all three pilot sites. Proposed adaptation measures included those to manage and reduce incoming solar radiation, such as use of exterior shades and screens for windows, replacement and upgrade of windows, use of cool roofs[60] and high-albedo building materials, and expansion of landscape and green areas to reduce urban heat islands within the industrial parks. Strategies to manage heat within the building include reduction of internal heat gains through lighting and equipment changes and upgrades to building HVAC controls and automation systems. Recommended management strategies include conducting detailed thermal comfort simulations for the sites to identify critical areas for improvement.

The IRIS project also includes access to a web portal and Climate Adaptation Support Tool (CAST), which is a web-based screening tool to assess vulnerability and risks related to climate change. The tool allows organisations to conduct a rapid, self-guided risk screening of their sites and provides support for past weather and future weather scenarios, evaluation of risks, identification of adaptation measures and development of adaptation plans.

Climate Risk Assessments

The aim of a climate risk assessment is to identify and reduce the risks resulting from climate hazards and explore opportunities to build adaptive capacity. Climate risk assessment methodologies generally include an examination of historical and projected climate data followed by a systemic assessment of associated hazards, vulnerabilities and impacts. Adaptation strategies and opportunities are then explored and evaluated based on the project, asset or site-specific criteria. This approach is fundamental to identifying and prioritizing adaptation strategies.

The engineering challenge

An engineering approach based on looking backwards – standards and codes.

When undertaking engineering design, either for new builds or retrofitting existing industrial assets or buildings, engineers begin the design process by considering the relevant standards, design codes, guidance and codes of practice.

Standards and design codes are documents that distil professional best practice and are drafted by recognised experts on the basis of establishing consensus and agreed terminology, often containing mandatory provisions and requirements. Guidelines and codes of practice are subsets of these documents and typically provide non-binding recommendations.

Typically, 'specification' standards and design codes are used to perform structural design calculations (ie to determine the structural loadings and ensure safe resistance to them) and to select as well as specify the desired materials' performance, such as, for example concrete strength, paint coatings, fixings, etc. During the service life of a design, specifications can also be defined to set operational and maintenance aspects, such as when to inspect, repair and renew components. For example, in the case of railways, these can specify how to manage the safety of track systems during periods of extreme heat by setting out requirements for detecting, reacting and responding to temperature-related hazards. Maintenance standards, operational rules and work instructions based on standards are often part of an organisation's asset management plans.

In an evolving risk environment, such as, for example, changing climate related risks over the life of a design 'decision', a specification standard can help identify the thresholds beyond which operations are no longer sufficiently resilient. At these points, the specifications themselves may need to be updated or transformational measures may need to be implemented.

Standards may be developed by individual sectors, industries or companies, where they can be used to set 'rules', such as specifications, test methods and governance procedures, including those for drafting new standards or updating existing documents. To address risks associated with climate change, examples of standards developed by industries and companies include the UK Energy Networks Association's ETR 138 Resilience to Flooding of Grid and Primary Substations and Network Rail's NR/L3/CIV/020 Design of Bridges. Both have sections covering future climate-related impacts.

However, many companies and engineers put emphasis on standards produced by a National Standards Body (NSB), such as the British Standards Institution (BSI) in the UK and Deutsches Institut für Normung e.V. (DIN) in Germany, as well as those drafted by regional bodies, such as, in Europe the Comité Européen de Normalisation (CEN) and Comité Européen de Normalisation Électrotechnique (CENELEC), and international standard bodies, such as the International Organization for Standardization (ISO). In the context of climate change, the primary engineering challenge associated with the documents produced by these organisations is their widespread reliance on historical weather data for establishing climatic parameters used in design calculations, as well as the substantial time involved in the process of updating them to account for possible future climates. The lengthy process is understandable, as this is a complex area, with many individual experts involved in establishing consensus and drafting and updating long-established documents.

As an initial step in addressing this challenge, CEN/CENELEC have in recent years engaged with the European Commission to build awareness of climate issues and published tailored guidance for writers of standards working in the infrastructure and buildings standards' area which explains how to incorporate climate change into standards[64]. Furthermore, as standards are updated and created, practical tools are required so that standards developers can understand and interpret climate information and effectively incorporate climate change data into the standards development processes. In relation to heat impacts, there are planned technical reports being drafted by CEN Technical Committee 156 on natural and hybrid ventilation systems in non-residential buildings and on ventilative cooling systems. These will focus largely on ventilation rates and therefore have a strong connection with wind velocity.

Similarly, in North America, the Standards Council of Canada (SCC) has taken an active role in increasing the consideration of climate change within the design, planning and management of Canadian infrastructure. A new step-by-step guide[65] was published in May 2021, supported by the SCC, that will help standards writers address potential climate risks and impacts across the life cycle of products, services, infrastructure and tests. The document helps standards professionals to determine if their work has any climate-related implications and, if so, what direction to take to address them. It also offers case studies and a list of other resources, such as climate datasets, tools and reports, including a Technical Companion to the Guide.

Many detailed engineering design codes also use or refer to weather or climate data in the specification of climate parameters, including temperatures. Take for example the EN 199x series of Structural Eurocodes[66], and in particular concerning thermal impacts – EN 1991 Part 1–5 : 2003[67]. As is normal in the codes, a national annex specifies shade air temperatures to be used in the design of structures. EN 1991-1-5 gives principles and rules for calculating thermal actions on buildings, bridges and other structures, including their structural members. The engineering challenge is that, as with many current standards used in design work, these calculations make use of historical climate / weather data which can be significantly out of date and particularly problematic in the context of climate change. Although the Structural Eurocodes are in the process of being updated to address this issue and discussions are in hand on how to account for future climate trends in the 'next generation' of the codes (the concept of including modification factors or project-specific criteria is being actively considered by the drafting committees), these revised versions will not be fully available for some years. It is therefore important to guide designers, operators and maintainers to seek weather and climate data for future conditions when specifying climate parameters, as appropriate to the life cycle of any industrial assets or buildings under consideration.

Internationally, North America and Canada refer to the ASHRAE guides for design, the key document being ASHRAE Fundamentals 2021[68], which includes climate data for over 9000 global locations along with guidelines for design and thermal comfort. Rather than providing an hourly climate file, ASHRAE provide design temperature thresholds (hottest and coldest) that are surpassed 0.4% and 1% of the time, together with the coincident wet bulb and dew point temperatures to allow HVAC equipment to be sized. The standard climate baseline for this data set is 1994–2014, although, given the number of locations, there is some variation due to poor data availability and it will not reflect more recent global heatwaves.

Climate data within the planned 2025 edition will be based on years 1998–2023, which will capture more recent warm weather events. The ASHRAE data does not include an allowance for future climate change; however, the 2021 edition does provide a short narrative on the topic.

In the UK, buildings are often designed in accordance with the Chartered Institution of Building Services Engineers (CIBSE) guides and, in the case of thermal comfort, CIBSE Guide A (2015)[69] is the most relevant, along with CIBSE TM52[70]. The latter sets out definitions of overheating, though specifically for naturally ventilated spaces.

CIBSE provide climate data files[71], which are commonly used for overheating design of buildings in the UK. These files consist of Test Reference Year (TRY) and Design Summer Year (DSY) formats, the former being a “typical” year and the latter a year with a “hot” summer. It is important, however, to note that these files have a climate data baseline of 1984–2013 and, as such, do not reflect the recent hotter summers in the UK. CIBSE also provide versions of these files which have been adapted using the UKCP09 climate change projections[72], but they do not as yet provide files for the more recent UKCP18[14] update. CIBSE has an active project to update these climate files to include a more recent climate baseline and the UKCP18 climate projections. The timeline of this work is expected to be around two-and-a-half-years.

In terms of hourly climate files, another commonly used source of climate data for global locations is the EnergyPlus Weather Data Set[73]. This data set provides ‘synthetic’ climate years for over 3,000 locations worldwide, specifically for use by designers to predict the energy usage of buildings. Again, this represents historical data and does not account for future climate projections.

Finally, when selecting climate data for use in the design of a building to prevent overheating, engineers should avoid using a single past year because no one year can represent the long-term climate patterns. Climate files, such as those provided by CIBSE in the UK and EnergyPlus globally, are typically created using data which is from at least a 25-year period to account for long-term climate statistics and are developed specifically for the purpose of predicting overheating and building energy demand.

Building codes and regulations are also an area where the use of historical data for determining climatic parameter input to design calculations is problematic in the context of climate change. For example, in Canada, the climatic design data used in the National Building Code (NBC) are based on several decades of historical data up to the recent past, as provided by Environment and Climate Change Canada (ECCC) through weather observations. There are no provisions or measures that explicitly account for future values that may result from climate change, the implicit assumption being that the past is representative of the future. To address this issue, the National Research Council (NRC) and ECCC have undertaken targeted research to develop future climatic design values of the NBC’s climatic design data[74]. The latter necessitated quantitative information on future climate change relative to buildings to be determined from climate model-based projections underpinned by a range of greenhouse gas emissions scenarios and climate model simulations[75]. Similar work is urgently required worldwide regarding national and local (for example, state or provincial level in federated nations) building codes and regulations.

Designers, operators and maintainers around the world need authoritative standards and engineering design codes based on up-to-date data for projected future climates, along with new methodologies and guidance, in order to design, build, operate and maintain future-proofed industrial assets and buildings. Given that projects being carried out today will experience considerable changes in the weather-related environment in which they are immersed during their lifetime, the use of climate data based on past climatic conditions must be urgently addressed by the engineering profession.


ENERGYGUIDE
15.5
FUJITSU
INVERTER

Sustainable net-zero cooling

Cooling is a significant contributor to global GHG emissions and therefore climate change. In parallel, it is also a fundamental requirement of strategies for adaptation to climate impacts from increased ambient temperatures and more frequent and intense extreme heat events. This dual characteristic presents society with a substantial challenge, in that as humans seek to adapt to higher temperatures, a rapid surge in demand for cooling could result in a feedback loop which creates a vicious cycle[H] that adds further to climate change. At the core of this challenge is the fact that artificial cooling, which is primarily delivered through the deployment of mechanical-based technologies (ie 'active cooling'), is today typically energy intensive, relatively inefficient, and a high emitter of CO_2 and other GHG emissions.

Human adaptation to higher local, seasonal and extreme (heatwave) temperatures therefore requires that, in common with other areas of adaptation, increased demand for cooling is met in line with the aspiration of the Paris Agreement to limit warming to 1.5°C. Cooling alone currently accounts for more than 7% of GHG emissions[76] as a result of 'direct' emissions produced by leakage and/or spillage of high Global Warming Potential (GWP) refrigerants/coolants (around 20% of the GHG emissions) and the 'indirect' emissions associated with the energy used in the equipment[77].

Given that, unchecked, these emissions are expected to increase significantly with demand drivers such as growing human population numbers; continuing urbanisation, industrialisation and digitisation; and rising incomes, achieving net-zero[I] in cooling provision is critical to realising the Paris Agreement targets. In the absence of market intervention, GHG emissions from cooling could rise 90% relative to 2017 levels by 2050[80] and it is anticipated that by 2030, 80% of the refrigeration and air conditioning (RAC) market will be located in developing countries[81]. This will necessitate the design and implementation of an approach to cooling globally in which considerations of mitigation outcomes are fully embedded in adaptation to heat, in essence a net-zero adaptation approach[82], or more specifically, a net-zero approach to cooling.

Potential pitfalls of Net-Zero Pathways

A key point to note when striving for net-zero adaptation is that to achieve a successful outcome to climate change mitigation strategies involving net-zero pathways, it is crucial that such pathways are carefully designed to ensure that negative emissions achieved through carbon removal are not simply substituted for approaches that involve reductions in GHG emissions. In short, that an over-reliance is not placed on promises of future negative emissions, and/or as yet unproven carbon removal technologies, rather than taking action to reduce emissions now[83]. Indeed, in the case of net-zero cooling, this requires a reduction of GHG emissions as close to zero as possible from both the direct and indirect emissions associated with cooling equipment during its entire life cycle: from resource extraction, manufacture, installation and operation; through to end-of-life decommissioning.

Any residual emissions (direct and/or indirect) are then balanced by an equivalent amount of carbon removal through, for example, offsetting against the carbon benefits of restoring forests and/or the use of DACC technology with carbon sequestration or utilisation[84]. However, in the case of the former, it should be additionally noted that when using natural systems such as forests, peat beds and wetlands for emissions offsetting, consideration must be made of the future performance of these carbon sinks in a world where climates are changing. For example, by accounting for impacts on carbon offsetting performance as a result of coastal flooding inundation and soil salination due to sea level rise[54], an increased frequency and intensity of wildfires, droughts and heat mortality events, pluvial and fluvial flooding, and changes to the atmospheric vapour pressure deficits leading to forest stress and increased attack threats from pests and pathogens.

As illustrated in **Figure 3**, minimising the GHG emissions from cooling to achieve an outcome as close to zero emissions as possible involves minimising the demand for artificial cooling through behaviour change and the use of passive cooling techniques[J] (Demand mitigation); the use of nature-based cooling solutions, such as water bodies and other heat sinks; making use of renewable and waste energy resources for cooling provision; using energy efficient technologies that avoid refrigerants with high GWP; and taking a life cycle analysis and circular economy approach to resource sourcing, design, manufacturing, deployment, operation, reuse, remanufacturing and end-of-life decommissioning.

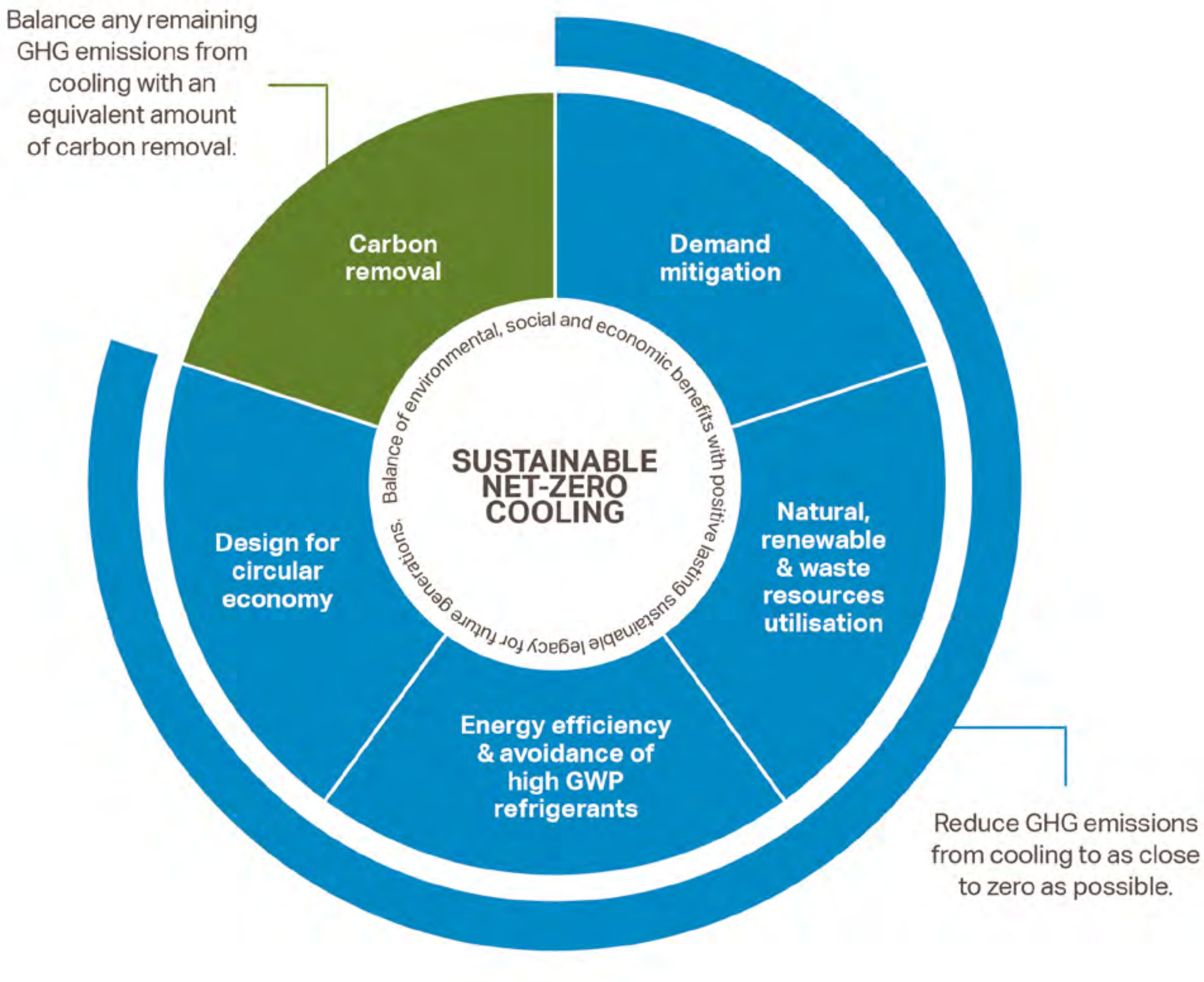
How engineers meet the challenge of adapting to increased temperatures through the provision of cooling across multiple sectors, including industry, will have important ramifications not only for future climates globally but also for broader aspirations for a sustainable human future. The goal must be to ensure cooling needs are met across a warming world within the limits of natural resources and ecosystems, whilst mitigating future climate change and wider environmental risks. Delivering net-zero cooling, whilst in parallel balancing environmental, social and economic benefits and leaving a positive lasting sustainable legacy for future generations, is Sustainable Net-zero Cooling (**Figure 3**). It necessarily must be accessible, affordable, financially viable, scalable, safe and reliable to help deliver societal, economic and health goals as defined by the United Nations' Sustainable Development Goals (SDGs)[85].

In short, in response to rising temperatures, the requirement for a successful adaptive outcome for humanity in the decades and centuries ahead is for nothing less than the delivery of sustainable net-zero cooling wherever and whenever cooling is needed.

Transitioning cooling provision away from 'business as usual' to sustainable net-zero cooling approaches and technologies[K] will require a paradigm shift to a different way of thinking that goes beyond simply acting on energy efficiency and electricity decarbonisation. What is needed is the development of fully integrated, resource-smart, system-level strategies to mitigate and meet cooling needs efficiently, sustainably and without GHG or other emissions.

At the core of this new way of thinking[86,87] there needs to be a clear recognition of the primary barrier to progress today, which is that when considering energy provision, the scope of current engineering and policy vision is typically constrained by defaulting to electricity and the use of batteries for storage. This restricted view misses the point that, in reality, the majority of the energy services required to support a modern society are in fact thermal (ie for the provision of heating and cooling). It therefore results in a sub-optimal energy system, potentially making the challenge of transitioning to net-zero and sustainability more difficult than necessary.

Figure 3: Sustainable net-zero cooling (reproduced with permission of Prof. Toby Peters, Dr Leyla Sayin and Dr Tim Fox)



Specifically, the engineering profession and policy-makers need to recognise that the provision of cooling could often be better served by (i) reducing the need for active cooling in the first place through encouraging behavioural change and deploying nature-based and passive solutions; (ii) aggregating demand; (iii) harnessing available thermal energy resources to meet thermal services – many of which are present in the local natural environs and can be sustainably utilised, or are rejected by other human processes and therefore currently regarded as 'waste'; (iv) using thermal methods of storage (for example, ice as an energy storage medium is a fraction of the price of a chemical-based battery) and; (v) creating new business models such as 'servitisation' – increasingly known as 'Cooling as a Service'[88] – to lift financial barriers on sustainable cooling provision and improve cooling access in urban as well as rural remote areas.

How can engineering respond?

Recent advances in the science of climate attribution have resulted in an increase in the number of extreme weather events, including heatwaves, that studies attribute to climate change. For example, the UK Met Office stated that as a result of climate change, the July 2022 heatwave in the UK had been made 10 times more likely to occur[89]. Such studies, together with the sober findings of the IPCC's Assessment Report 6[7,10], AR6, published in 2021–22, have increased the awareness of society to the urgent requirement to adapt at pace, and engineers, along with a myriad of allied professions, need to respond.

In the case of engineering, through efforts of bodies such as the IPCC, UNFCCC, and the UK's Committee on Climate Change, engineers and their clients around the world are becoming increasingly aware of the potential deficiencies in engineered infrastructure and the built environment due to design criteria reliant on historical weather patterns. The updating of national and international standards and design codes to include climate change considerations, such as, for example, through the application of the CEN Tailored Guidance for Standards Writers[64] and the programme to update the next generation of Eurocodes, will certainly have a role to play in helping engineers to build resilience to future heat impacts. However, as noted earlier, the time frame associated with the process of updating all the relevant standards and codes will be long and, in the meantime, engineers will be designing industrial assets and buildings that will be in operation for decades to come, designs that will be exposed to considerably different climatic conditions to those upon which current methodologies and tools are based.

Climate Data and Flawed Financial Investments

During early project development for industrial plants, mass and heat balance design assesses the process flows and energy flows, invariably in the form of thermal energy. Designers need valid predictions of climatic temperature, humidity and availability of water in developing their heat balance plans for assets they are designing. These predictions need to extend beyond the realistic operating life of the asset. If design decisions are educated by inaccurate predictions or historical regional climate data, then the financial investment decisions along with the environmental impact assessments will invariably be significantly flawed.

So how can engineers respond to this challenge and avoid future claims of professional negligence in design work for not considering the impacts of climate change or, more specifically, the increases in ambient temperatures and the frequency and intensity of extreme heat? In short, beyond understanding the issues, it is down to design engineers and their employers/clients to make use of the available science, engineering knowledge and climate projections, drive research, development and innovation, and ensure that potential future temperatures are accounted for as well as 'mainstreamed' into the cycle of design, build, operate, maintain and decommission.

Climate Adaptation in Design

Mainstreaming climate adaptation in design projects requires a 'line of sight' from the heads of agreement to the delivery of industrial assets and buildings, covering all stages through design, build, operate, maintain and decommission. However, although it is relatively easy to agree at an early stage of project procurement that the design needs to be 'resilient' to hazards, the reality is that heat impacts, vulnerability and risks cannot be addressed using many current standards and design codes, due to their reliance upon data for the past climate.

What is needed is some way that compels or otherwise persuades governments, property developers, owners of industrial assets and buildings, financiers, lenders and those involved in the procurement process (design consultancies, construction companies, operators, maintainers), that a range of climate change-related considerations are relevant at all stages. In this regard, international standard ISO 14090 Adaptation to climate change – Principles, requirements and guidelines[90] can help in that it provides a high-level framework that addresses key considerations. These include governance, leadership, organizational maturity and capability, impact assessments, adaptation plans, integration into existing policies, strategies and plans, skills, resources, indicators, monitoring and evaluation and learning feedback. Published in 2019, ISO 14090 was the first international standard to specifically relate to climate change adaptation and its application is intended to be alongside other organizational priorities. It states that its "approach is relevant to all sizes and types of organizations where their activities, products and services might be threatened by, or in some cases able to take advantage of, climate change." As well as setting out general best practice at a high level for drafting effective adaptation plans, it is recognised as having a framework that is being used to guide the development of further adaptation standards. ISO has since published ISO 14091:2021 Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment[91]. Other standards to support ISO 14090 in more detail are planned.

There are also many advantages to adopting a policy of adaptation at the renewal and / or refurbishment stage for existing assets – replacing life-expired buildings or installations with designs that are 'future-proof'. Furthermore, a policy of 'build back better' after weather damage can be beneficial – rather than one of replacing 'like for like' – where industrial assets and buildings are designed with future hazards in mind. For example, in the case of public infrastructure, this concept is part of Network Rail's strategy: "when weather events cause catastrophic asset failure such as collapse of a sea wall or scour damage to a bridge, [Network Rail] commit[s] to replacing like for better rather than like for like"[92].

Engineers should think about 'entry points' for adaptation. Each stage of a project carries considerable scope for reviewing decisions, as well as workflows, and thoughtfully linking to relevant standards and guidelines at appropriate stages (the entry points) throughout the process. Clients have considerable leverage and can push the 'line of sight' concept so that what is seen as necessary at the outset of a discussion about a project translates to fruition during and after the delivery phase. Key areas to help in this could be:

- making the best of existing standards and design codes by using the CEN Tailored Guidance[64] to develop site-specific weather hazard parameters that are compliant with their requirements but provide better resilience.
- using UKCP18[93] or the EU's ClimateADAPT[94] (or equivalents in other countries) for future heat impacts related data.
- considering an adaptation pathways approach for new / replacement / refurbished assets to deal with the issue of uncertainties.

With regard to the latter, a major barrier to adaptation progress often cited by engineers and their employers/clients is the uncertainties that are inherent in climate modelling, from those associated with choices of emissions scenarios through to those resulting from an incomplete understanding of the detail of complex physical processes, such as, for example, the collapse of ice shelves in West Antarctica. This often leads to a tension in design work between the engineer's inherent desire to provide a fully robust and safe design and the employer's/client's concerns regarding project costs, delivery timescales and other economic considerations. How can engineers and standards/design code developers account for these uncertainties?

One factor to consider will be the life cycle[L] of an industrial asset or building. Those that are currently in place will generally have been designed to cope with ambient and extreme temperatures derived from historical climate data, and new builds or replacements/ refurbishments/extensions can be designed – with the benefit of the CEN Tailored Guidance[64], for example – to take into account future heat hazards. However, to ensure that uncertainties are accounted for fully in both cases, the life cycle of the asset, infrastructure or building should be considered.

BSI standard BS 8631:2021 Adaptation to climate change – Using adaptation pathways for decision making – Guide[95], published in 2021, helps in that it offers a new approach to dealing with uncertainty, termed 'adaptation pathways', which is being increasingly used in practice when designing relatively long-life infrastructure. The adopted process makes use of staged interventions over time, each of which is assessed for compatibility with later interventions, resulting in a long-term, effective economic planning strategy.

The BS 8631 methodology involves a nine-step process that examines changes in climate hazards over time and embeds the processes of adaptation into long-term strategic planning. Adopting the adaptation pathways approach encourages the exploration of a range of potential actions at future decision points, including transformative adaptation[M]. This adaptive, iterative approach can be seen as preferable to a 'design life' approach, in that the former allows for changes over time and associated costs to be incurred as and when necessary, whereas the latter results in only one 'belt and braces' design that caters for many uncertain future scenarios over its design life and incurs all the costs (potentially unnecessarily) upfront. A design life of, say, 50 years might, for example, incorporate so much allowance for the uncertainty of future ambient and extreme temperatures that the industrial asset or building becomes unaffordable to the client at first cost. Such an outcome could lead to decision-making that avoids adaptation measures being built into the project. By using an adaptation pathways approach, passive provision can be made at the initial construction stage for future enhancements, should they be required. This can make more sense where it is assumed that climate science, along with an understanding of the asset or building's response to climate change impacts, improves over time, thereby reducing the level of uncertainty.

Other areas the engineering profession should consider include:

- Thinking at a systems level and about 'criticality' in interdependencies – society depends upon infrastructure systems that are interlinked; for example, energy and water supply, waste management, transport and communications technology are all interdependent. The failure of any systems, sub-systems or individual components thereof in one such sector can impact those of other dependent sectors and in some cases lead to cascading failures. Further, some dependencies will be more critical than others and priorities should be assessed in this regard for establishing failure risk mitigation strategies. Addressing this issue requires engineers to adopt 'systems thinking', and ISO 14090[90] recommends such an approach when scoping the coverage of an adaptation plan.
- Good practice in planning – evaluation of, and changes to, existing planning laws are required for new builds to reduce exposure to climate hazards, including heat impacts, and new planning guidance is needed for retrofitting existing infrastructure.
- Capacity-building – developing 'adaptive capacity' is a fundamental part of an adaptation strategy and in this regard an assessment of an organisation's capabilities, including those of the decision-makers, can be useful. Tools such as Capacity Diagnosis and Development (CaDD) can help streamline this process. Using CaDD, training needs can be identified and training programmes tailored to improve adaptive capacity.
- Monitoring, evaluating and making the right changes throughout the whole project delivery process.

One technical area where more research, development and innovation focus are needed to inform engineering design is the 'industrial heat island' phenomenon, which is similar in character to the more widely known 'urban heat island' effect. There is a significant knowledge base in place related to the latter, which has been attained through research involving actual temperature and humidity measurements, as well as computer modelling. This has led to an understanding of the impacts of human-produced heat (anthropogenic heat) and the capacity of building materials (urban morphology) to absorb, store and emit heat energy in the urban landscape. Analysis is, in this regard, often completed for city-sized areas and the modelling typically takes account of parkland, greenspaces, residential and commercial areas.

One recent industrial-focused study[96] which considered the phenomenon in the Angul-Talcher region of Odisha State, India, utilised an adapted single-layer urban canopy model (WRFUCM) technique. Even with the declared limitations of the work, the industrial heat island predictions suggested a 1.7°C daytime increase, and a 5.88°C night-time increase, in temperature in the industrial areas compared to their surrounding environs. Odisha State is located adjacent to the Bay of Bengal and experiences its hottest weather in May, with mean daily maximums around 36°C and night minimums of around 26°C, and as such a predicted industrial heat island night-time temperature increase of just below 6°C is a significant increase.

The prediction methods used in the study were generated at a macro scale for a major industrial region and used to inform regional climatic modelling. They were not, however, suitable for providing detailed estimates of air temperatures local to equipment located within an industrial process plant with multiple heat sources. In the case of such assets, elevated air temperatures stem from many sources, including the following:

- regional air temperatures;
- solar radiation;
- hot process equipment (pipes, tanks, vessels, etc.) emitting heat by radiation and convection;
- combustion equipment exhaust stacks;
- stored heat in concrete structures and paving;
- air emitted from air-cooled heat exchangers.

Micro-scale modelling should be utilised to determine local air temperatures in process plants to inform the design and layout of industrial facility assets. Computational fluid dynamics (CFD) is used extensively in data centre plant modelling to optimise room layout and design (for example, orientation of chillers, flues on generators, design features such as blanking, louvres and gantries, etc.) to avoid re-entrainment of hot air into the plant, with a focus on mitigating risks to equipment performance. Similarly, it can be used to model the air temperatures and flows around industrial plant to optimise their layout and design. Critically, through such an approach the asset's cooling system performance and efficiency will also be optimised.

The case study related to oil refinery design on the following page provides further insight into the need for engineers to account for industrial heat island effects in plant and equipment layout. Clearly, in a world where ambient temperatures are increasing and extreme heat events are becoming more frequent and more intense, understanding the industrial heat island effect is critically important to the design of new industrial assets and refurbishments of those that already exist. In this regard, action that should be taken to tackle this knowledge and design methodology gap includes:

- Issue isotherm charts for main industrial cluster areas to include full 'in-sun' data in addition to the traditional 'in-shade' data. Designers and operators will require future estimates based upon the best available predictions, with probabilistic ranges defined.
- Use of micro-scale industrial heat island modelling tools by designers to optimise the siting and layout of process plant cooling systems.
- Use detailed computational modelling tools, such as, CFD to determine the optimal location and orientation of plant equipment to increase the asset's resilience and the likelihood of continued performance during hot weather events.

Beyond the specific case of industrial heat islands, to ensure that the engineering design of industrial assets and buildings is 'fit-for-purpose' in a world that is becoming warmer, the profession needs to:

- Bring sector bodies, regulators and knowledgeable consultants together to develop sector-specific adaptation guides which clearly communicate that designing new assets and buildings, or assessing those existing assets for refurbishments or modifications, using current standards (or worse, using standards applicable at the original build date), will fail to identify longer-term vulnerabilities to heat impacts.
- Develop awareness and training programmes for operators, asset engineers and designers to communicate the vulnerabilities that exist and provide guidance on pathways to resilience.
- Encourage high hazard industry regulators to mandate operator assessments of extreme heat risks alongside other climate threats within their license-to-operate application, as well as to carry out a gap analysis between original design specifications and more recent future climate data. Operators must determine thresholds beyond which operations are no longer sufficiently resilient and establish adaptation plans to create resilience.
- Consider 'build back better', rather than 'like for like', when replacing aged assets to ensure that they are fit for future service.

Case Study

Industrial heat island impacts on oil refinery design

Oil refineries require significant heat input to distil crude oil into products and to crack lower value, longer-chain hydrocarbons into higher value, shorter-chain products. Subsequently, they then require significant cooling to condense and cool products for storage and transportation.

During the European oil refining boom of the 1970s, plants were designed based upon the prevailing weather conditions experienced in the 1960s and 1970s. A UK-based refinery's dry air-cooled heat exchangers were designed for a maximum air temperature of 21.1°C, but 40 years later when the refinery underwent significant refurbishment, new air-cooled heat exchangers were being designed for 27°C air temperatures.

In the intervening years, the ambient temperatures had not risen by 5.9°C. Data from the nearest weather station indicates an increase in summer average peak temperatures of 0.9°C over the period. So why did the engineers decide to increase the design basis by 5.9°C?

The decision was based upon 40 years of plant operating knowledge. To understand the engineers' rationale, it is necessary to consider the effects of both high ambient temperatures and prolonged periods at elevated temperature.

Short-term high air temperatures experienced on a single hot day will normally occur over 4 to 6 hours in the afternoon and lead to reduced cooling ability, which can be managed by increasing flaring of light products (those that are harder to condense) or reducing throughput. The operations can return to normal during the evening as the sun goes down.

In 1970s and 80s, flaring of excess material was an acceptable practice across the world's refineries. It is only in the last few decades that flare losses are controlled by refiners and are strictly regulated in many countries (flaring results in significant GHG emissions). As such, modern plant design cannot rely upon the availability of a flare system to accommodate short-term high temperatures.

Since the 1970s, the number of prolonged periods of elevated temperature has increased, extending to several days in Northern Europe, and, in addition, the number of cool summer days has reduced. Prolonged periods of high temperatures with fewer cool summer days means that overnight temperatures remain elevated. Often when products are run down to tanks, it is possible to mitigate for hotter products during a hot day by the cooler products at night, or the next cooler day, giving an acceptable mean tank temperature. Unfortunately, when high temperatures are experienced for prolonged periods, this averaging is unavailable, and the only option will be to reduce the feed rate, which leads to lost production with the associated impacts on the asset's economic performance.

In specifying the maximum design air temperature as 21.1°C, the designers underestimated the heat mass effect resulting from the refinery operations and the radiant heat of its structure. Traditional oil refinery design positions the air-cooled heat exchangers at an elevation above the process pumps and pipework. As a result, the heat emitted from the process pipework and equipment, along with the heat stored in the structural mass and concrete, acts to pre-heat the air before it is drawn into the air-cooled heat exchangers, therefore degrading their performance from the design curve.

The engineers 40 years later recognised this effect and, by taking measurements and assessing the thermal performance of existing equipment, identified the need to increase the design temperature to 27°C. The impact of urban areas and anthropogenic emissions in the creation of urban heat islands is well understood; however, a greater understanding of industrialised heat islands is needed by design engineers working in the sector.

Sustainable net-zero cooling in practice

Work to increase the sustainability of cooling today is primarily focused on improving individual technologies. More specifically, it is focused on transitioning away from high-GWP refrigerants to natural or ultra-low variants and increasing equipment efficiency. In the case of the former, a significant scale-up is required in the roll-out of cooling units using alternative refrigerants, thereby reducing the direct emissions resulting from leakage and/or spillage during use and end-of-life disposal. Overall, these direct sources are estimated to be responsible for as much as 20% of the total emissions from commercially available cooling equipment[77]. In the short term, given that around 90% of direct emissions from refrigerants occur at the end-of-life phase, better disposal practices can significantly reduce cooling emissions from equipment that is already in use[97], particularly in developing countries. Additionally, about 60% of total hydrofluorocarbon (HFC) consumption in the cooling sector arises from topping up of refrigerant leakage during the servicing of installed cooling equipment[98], so strengthening the servicing sector could also reduce leakage through improved maintenance of the existing and future equipment stock.

Importance of Maintenance and Servicing

Under the Montreal Protocol[99], it was recognised by TEAP[N] that "the impact of proper installation, maintenance and servicing on the efficiency of equipment and systems is considerable over the lifetime of these systems while the additional cost is minimal. The benefit of proper maintenance is considerable. Appropriate maintenance and servicing practice can curtail up to 50% reduction in performance and maintain the related performance over the lifetime"[100]. Directly related to this, effective optimisation, monitoring and maintenance can, in fact, reduce total cooling GHG emissions by 13% and deliver substantial energy savings of up to 20% over the equipment lifespan[76]. Additionally, the lifetime of equipment can be improved, and the risk of breakdown can be reduced, through better design, installation, maintenance and servicing practices, thereby preventing downtime and early replacement of equipment. For example, the Indoor Air Quality Association estimates that regular HVAC maintenance can reduce the risk of breakdowns by as much as 95%[101].

The principal challenge in improving energy efficiency is the pace required to make improvements, which is far beyond what has been historically achieved by cooling technology and equipment developers through a 'business as usual' approach. In this regard, overcoming technical constraints to the speed at which efficiency is improved is essential if real, tangible progress is to be made against a background of rapidly growing global demand for cooling equipment. The Global Cooling Prize has recently illustrated what, given appropriate incentivisation and a concerted effort, can be achieved in overcoming such technical constraints in the case of room air conditioners**[O]**[103].

In the case of industrial assets, such as those of the process industries, the introduction of adiabatic cooling can offer a potential cost-effective route to increased plant efficiency[104] in periods of hot weather with low humidity. The technique uses the spraying of water to pre-cool the supply of air to the condenser of an air-cooled heat exchanger. Reducing the inlet air temperature increases the condenser's effective capacity and thereby reduces the work required of the compressor driving the refrigeration cycle. The decrease in energy consumption through the increased efficiency reduces the plant's operating costs. Typically, the capital costs payback period for installing the additional equipment to deliver adiabatic cooling on a process plant is around 2 years, and additional financial savings are achieved through the reduced loading of the compressor, which cuts maintenance costs and extends its operational lifespan. It should be noted, however, that increased costs can be incurred due to structural degradation from corrosion and the build-up of scale deposits on cooling surfaces, as well as increased water consumption. The latter also needs to be carefully considered in the context of future increases in the frequency and severity of droughts.

Broader work on the energy efficiency of HVAC and refrigeration equipment used in the process industries and industrial buildings is exemplified by the research and development work being undertaken at IIT Bombay in India. In this regard, the team in the Department of Mechanical Engineering's Heat Pump Laboratory[105] are pioneering a range of energy conservation and waste heat recovery techniques to improve the energy performance and sustainability of multi-utility heat pumps, as well as super heat recovery and waste heat recovery systems. Improvements are achieved through the application of novel technologies, including multi-stream vented double-wall tube-tube heat exchangers; sorption refrigeration systems; and rotating contacting disk-based humidifiers, air washers, cooling towers, evaporative precoolers and wastewater evaporators. Energy efficient cooling equipment based on these techniques has been proven by the team on processes used in the dairy, pharmaceutical, textile and chemical processing industries and their associated premises, often with paybacks in the range of 3 to 12 months. A judicious combination of multi-utility heat pumps with built-in thermal storage enables multiple utilities to be catered for in flexibly using a single system. This offers the advantages of lower initial and operating costs, lower footprint, and lower refrigerant charge, and the overall effect is significantly lower embodied energy and environmental signature.

One key barrier to the uptake of 'best available' high energy efficient technologies, however, is the fact that in general they often require a greater upfront capital investment cost when compared to incumbent cooling options. While per-unit manufacturing costs and market prices may be higher, economic cost savings are often possible from new equipment that meets higher energy efficiency, but the principal issue is that these cost savings are typically realised over a relatively long time frame. The latter can discourage investment, especially in countries which have a high cost of capital and less developed economies, where quick returns are expected to drive growth.

Other adoption barriers that may slow down the transition include:

- a lack of relevant standards and regulations;
- cascading of sub-standard equipment from the Global North into developing countries (for example, 75% of the refrigerators imported into Ghana from 2004 to 2014 were second-hand[106]);
- weak monitoring and enforcement regimes to stem the availability of counterfeit refrigerants;
- insufficient coordination and cooperation;
- the additional training required to implement and maintain the new technologies; and
- insufficient trust in new, innovative technologies that have low market penetration.

These barriers need to be addressed through market interventions, such as awareness raising, approaches to procurement practices that are tailored to individual countries, financial levers for manufacturers, increased price transparency and innovative business models.

Although the work that is taking place on improving refrigerants and equipment energy efficiency is certainly important, when approaching the challenge of energy supply and meeting consumption demands more broadly it is critical to establish a framework to determine prioritised energy system actions. This requires consideration of the most sustainable options first and the least sustainable last, with a sustainability-graded hierarchy of intervention classes between these two boundaries[107].

Such an approach can often result in the prioritisation of actions that are counter-intuitive to those that are initially thought to be important. For example, in the specific case of meeting future energy demand for the provision of cooling, traditional electrical efficiency improvements are key in the short term, but for longer-term sustainable system design such a hierarchy leads to a consideration of an alternative approach of reducing demand first, then seeking opportunities to use heat sinks and thermal energy from waste, free or low-grade sources, to offset the need for electricity.

Within the context of this hierarchal framework, the focus fundamentally shifts from energy efficiency to the efficient use of all available energy resources, and the challenge of electrical efficiency becomes a third-stage consideration.

In the case of industrial assets and buildings, the anticipated future demand for cooling will not be met sustainably by simply transitioning to new refrigerants and installing higher efficiency HVAC and process cooling equipment in plants and premises. Instead, a transition to a new approach based on the efficient use of energy resources needs to begin, and this will involve:

1. Reducing the need for active cooling in the first place through encouraging behavioural change and deploying nature-based and passive solutions, such as leveraging natural ventilation, tree shading and bodies of water in close proximity, etc[P].
2. Aggregating multiple demands for efficient use of supply, by for example using district cooling network infrastructure.
3. Harnessing available thermal energy resources to meet thermal services, many of which are present in the local natural environs and can often be sustainably utilised. For example, by making use of ‘free’ cooling resources, such as cold water from local rivers, lakes, underground aquifers or ocean sources which can be passed through a building and/or process plant to provide cooling[Q].
4. Harnessing thermal energy resources rejected by other human processes and therefore currently regarded as ‘waste’ – waste thermal streams from one process can be used to provide valuable thermal services to another process, thereby replacing primary energy consumption (for example, see the case studies on the use of industrial waste cooling from LNG regasification and cooling water heat recovery use for district heating).

5. Using thermal methods of storage and the utilisation of thermal energy carriers instead of electricity and (chemical) batteries, thereby unlocking otherwise redundant resources of renewable or waste energy and boosting system flexibility by enabling cold and heat to be used where and when needed.

Specific examples of reducing the need for active cooling in industrial premises through passive design strategies, to effectively moderate the overheating risk of occupants, equipment and processes, include consideration of the orientation and shaping of buildings. In the northern hemisphere, implementation of this approach involves accounting for shading from the high, southern solar angles of the mid-day summer sun (northern solar angles in the southern hemisphere) and the low, western solar angles of the afternoon/evening sun. Long east-west orientation, horizontal overhangs on southern facades (northern in the southern hemisphere), and external shading (eg vertical fins, landscaping) or window treatments on western facades are effective for rejecting summer heat gains and reducing cooling load during peak cooling conditions.

The most important passive system in a building is the enclosure and facade system. Thermal insulation and thermal mass can allow a building to reduce and shift the timing of peak cooling loads, while the choice of material for the facade impacts on the building's ability to reflect solar heat gains. Industrial buildings often have large, darkly coloured and exposed rooftops (with poor insulation) which can be a significant path for heat gain. High-albedo (light-coloured) surface treatments or heat-reflecting smart tiles should be selected to mitigate these unwanted heat gains[108]. Green roofs (ie roofs covered with vegetation), can also provide additional protection from solar radiation. Tree canopies surrounding buildings can provide direct shading and may also result in neighbourhood cooling by reducing urban heat island effects of hardscape designs.

Natural ventilation can also be an effective means of rejecting internal heat gains when outdoor temperatures allow. Clerestory vents, double-sided cross ventilation and night-time flushing can be effective methods of cooling. The variation of temperatures throughout the day can also be exploited to provide cooling through the storage of coolth at times when temperatures are low (typically during the night) and its subsequent use for absorbing heat when temperatures are high.

Although some passive strategies can be difficult to incorporate in existing buildings when the orientation, shape, materials and façade are already fixed, retrofits can readily incorporate shading, high-albedo surfaces and natural ventilation. The cascading benefit of passive design measures are that, as well as adapting to climate change, they typically also result in reducing carbon emissions, thereby contributing to the mitigation of climate change.

While strategies to passively cool buildings themselves are essential, it is important to also consider the impact of the building's context and surrounding environs on managing and moderating the impacts of extreme heat. Industrial buildings are often located in zoned industrial parks and dense urban areas, where lack of vegetation and abundance of hardscape can create significant heat island effects. State-of-the-art materials, such as improved paving materials on streets, can help reduce heat impacts, and urban vegetation can have a cooling effect on daytime temperatures at the site and across a wider spatial area[109]. The latter simultaneously offers numerous co-benefits, such as carbon sequestration, improved air quality and stormwater management, and increased biodiversity. Care should, however, be taken in such schemes to select tree and plant species that can withstand current and future extreme temperatures and drought conditions, as well as climate change-induced stress mortality due to changes in atmospheric vapour pressure deficits and increased threats from pests and pathogens.

Passive Performance Energy Modelling

The approach to designing new buildings and retrofits for passive thermal resilience is relatively straightforward. However, the challenge is to optimise these components and strategies in the early design stages. The use of energy modelling software offers opportunities to evaluate building performance during extreme temperatures and implement energy and cost savings. Time-based metrics are recommended in evaluating thermal resilience, including thermal autonomy and passive habitability[110]:

- Thermal autonomy is a measure of the fraction of time a building can passively maintain design conditions without active systems.
- Passive habitability is a measure of how long a building remains safe to inhabit during extended periods without power which coincide with extreme weather events.

This approach emphasises passive measures and resilience and can be evaluated using relatively simple, fast and accurate simulation tools.

It should, however, be noted that building simulations to assess energy and thermal performance have typically been conducted using historical weather data, which does not consider the future effects of climate change. As architects and design engineers aim to adapt, it is important to work with up-to-date projections of future climates as well as methodologies to account for the associated uncertainties.

Integration of Thermal Storage to Unlock otherwise Redundant Resources

Heat rejected from refrigeration systems can be used synergistically for heating, thereby providing significant energy and emission savings and leading to overall emissions reductions. With the integration of thermal energy storage, heat can be stored when refrigeration loads and heating requirements are mismatched, and the stored heat can be made available for use later. One study of refrigeration system heat recovery for space heating provision in supermarkets found that through such an approach thermal storage increases the potential of heat recovery by 11–12%[111].

Thermal energy storage systems can also be used to absorb excess power from intermittent renewable sources, such as wind or solar, and store it as cold and heat for use in a wide range of domestic and commercial applications as well as industrial processes.

A more holistic systems approach is necessary to meet the challenge of delivering sustainable net-zero cooling and tackle the barriers to success in the most effective and efficient manner. While optimising the components of the sub-systems of a whole system of systems is important, this reductionist approach neglects to account for the interdependencies that exist between economic decisions, available energy resources, technology choices, climate change mitigation and adaptation strategies and social, cultural and political systems.

Consequently, it results in a sub-optimal outcome. A whole systems approach considers the full range of drivers and feedback loops within a system and, in the case of cooling specifically:

- aims to minimise the demand for active cooling via the integration of passive cooling techniques and approaches as well as behavioural change;
- helps make sure individual cooling technologies are supported by the broader infrastructural landscape in which they are embedded (such as manufacturing, energy, transport, waste management, etc.), that interdependencies are understood and managed and that components work synergistically together;
- helps governments/policymakers/financiers to identify where current policy and regulations, alongside monetary and fiscal interventions, perform well, and;
- identifies where barriers exist that require intervention or need interventions to be redefined, realigned to the goal of net-zero and/or improved to enable the uptake of sustainable net-zero cooling solutions and accelerate transition.

This approach also supports the wider energy system decarbonisation by:

- reducing the investment need for increased power grid and generation capacity;
- freeing up limited renewables capacity for other uses;
- reducing peak energy demand, and;
- creating more room for intermittent renewable and waste thermal energy sources through thermal energy storage systems.

Case Study

Heat recovery from glass foundry cooling water into a district heating network

There is a significant opportunity to utilise waste heat from local industry to accelerate industrial decarbonisation and help meet net-zero emissions targets. Heating represents 37% of the UK's total carbon emissions[112] and is primarily produced by fossil fuels, as most residential homes are heated by gas-fired boilers. From 2025, new homes in the UK will be banned from installing gas boilers, and clean technology such as heat pumps, powered by electricity, will be used instead[113]. The UK has significantly reduced the electrical grid's carbon intensity through the generation of clean renewable electricity, mainly from wind and solar renewable energy systems. Low-carbon heat pumps connected in a district heating network enable the sharing of heat between different applications or between buildings in a neighbourhood and allow for heat recovery from local sources, such as heat from industrial processes. Integrating industrial heat into district heating networks can potentially reduce the industry's energy consumption, whilst meeting local buildings' heat demand.

A feasibility study was carried out for an urban area in Yorkshire, aimed at driving clean growth and decarbonisation in local industry together with investment in low-carbon energy systems. The Smart Local Energy System (SLES) consists of a low-temperature heat network with large, decentralised heat pumps to raise temperatures to those required in the connected buildings/dwellings. The heat source is low-grade waste heat from a local glassworks which is readily accessible with minimal disruption to 24/7 operations. There are a range of heat recovery opportunities from the glassworks; for example from the furnaces, electrostatic precipitators and cooling towers. However, to avoid any interruption to the process operations, the focus of this study was heat recovery from lower-temperature process cooling water that is collected in lagoons on-site via a network of gullies.

Data was gathered in the winter months to monitor the temperature in two different site locations and showed an average 28°C, within a range of 17–48°C. Heat recovery was estimated at 7MW, based on a flow rate of 178 l/s, but this would vary depending on temperature fluctuations. The scheme considered thermal storage and the integration of a 20MW solar PV farm. The results show that it is possible to decarbonise large parts of the borough, including their social housing stock and 1,500 new homes. In addition, using mine water as a means of storing and recovering heat allows seasonal thermal energy storage to act both as backup and top-up to the heat available from the glassworks.

The network would be built in phases, connecting 2,491 properties, including all the new-build developments and some existing buildings, such as schools, social and private housing. The techno-economic modelling has shown an internal rate of return of 7–9% when the network is supplied by the large 20MW solar farm, providing savings of 5,241 tonnes CO_2 per year on average. This SLES approach uses natural resources and builds on local industry to accelerate economic regeneration, paving the way to net-zero carbon emissions.

Case Study
Liquefied Natural Gas cold recovery

One area of the process industries where there is significant interest in the utilisation of a waste thermal resource and the application of systems thinking is liquefied natural gas (LNG) Cold Recovery, where an available cold source is largely untapped[86,87]. **Figure 4** illustrates the LNG gasification and regasification process that is used in the absence of a pipeline to facilitate the transport of Natural Gas (NG) from source to market. It shows the point in the supply chain at which a large amount of cold energy is released (and typically wasted) – around 240 kWh per tonne of LNG. This untapped cold energy could be exploited for multiple applications, providing an opportunity to recover part of the energy consumed at the liquefaction stage, thereby improving energy efficiency. Work to date[114,115] suggests aggregation and systems approaches to create new downstream markets for the waste cold could deliver significantly higher returns, along with economic resilience and monetisable environmental wins through decarbonisation of cooling and energy services.

Although there has been extensive research on LNG cold utilisation technologies with various applications, the implementation level is still low. The available cooling from LNG regasification is utilised in a few terminal facilities around the world but historically this has been limited to industrial or commercial processes that are integrated with the main facility.

The major developments in this area originate from Japan, where several power plants using cryogenic energy recovery have been operating for a long period[116]. More recently, some district cooling projects have been developed or commercial models tested but there are several challenges to stand-alone business concepts, especially in emerging markets[117,118].

The temporal and spatial limitations of this process, which is dependent on intermittent periods of regasification at terminal sites, can be overcome by converting the waste cold into a vector or form that is storable and transportable[86], allowing cold to be used at distant locations on demand and in aggregated services.

Research teams in a number of countries have explored system-level approaches using novel energy vectors to decouple the supply and demand by time and location, so as to simultaneously and sustainably meet:

1. A range of more distant cooling services across the built environment and transport.
2. Real-time demand and pricing signals.
3. Grid-based services, such as firming capacity and time-of-use management.

Figure 4: Simplified diagram of a typical LNG supply chain

Knowledge transfer – education and training

In response to the challenges of a warming world, current and future engineers will need to be creative, innovative, collaborative, resilient, and socially adept with excellent communication skills. The latter is absolutely vital if engineers are to help ensure industry, politicians, policymakers and the general public understand the broader societal impacts of increased temperatures, the implications for productivity levels and the broader economy, and the potential engineered solutions for adapting to heat and building capacity for resilience. Many of the challenges to be tackled will be global in nature and the approaches and technologies needed to tackle them will, in many cases, also be global, requiring engineers to have well developed skills in international collaborative working[119].

The current technical training and education systems were designed to operate in a climate-stable, cooler world. It is essential, therefore, that not only that basic climate change knowledge is taught throughout all the engineering disciplines, but that considerations of the impact of a warmer climate, adaptation measures and sustainable design are also included to ensure the basic working knowledge of graduates is 'fit-for-purpose' to address the substantial global challenges faced by society. Curriculums should be linked to the SDGs[85] and the Paris Agreement[4]. Evidence of this is emerging at the research level; however, it is crucial that these skills are taught at undergraduate and apprenticeship levels, and more needs to be done. This requires action from funding bodies, the Engineering Council and professional institutions to ensure these topics are deeply embedded into programmes.

Beyond the traditional academic training routes, the engineering profession must rapidly inspire, attract and retain an expanding and more diverse range of people with non-traditional academic profiles to develop engineers in the timescale needed to meet the challenge. This means making education and skills training more accessible, relevant, responsive and transformative to new cohorts. Upskilling and continuous professional development also have an essential part to play in redefining the role of the profession and allowing greater talent mobility between businesses, academia and other organisations in both the public and private sectors.

Thought needs to be given to how to access these courses, including part-time and virtual learning options, and the skills required to address current and future gaps in provision that need to be filled if the profession is to deliver the necessary changes. This will require the profession to develop a deeper understanding of the future role of engineering in society and, therefore, the skills, resources and training to achieve this, much like the work carried out by the High Value Manufacturing Catapult and the Gatsby Foundation on the Skills Value Chain[120]. Additionally, the profession needs to build an evidence base for successful, impactful, transformative interventions in schools, colleges, industry and broader society. It must deliver a roll out of these to scale through strategic collaborations that create an education, skills and accreditation system 'fit for purpose' in meeting the challenges of a warmer world throughout the supply chain.

Skills and Capacity for Cooling

Achieving a sustainable net-zero cooling economy and meeting increasing cooling demand – if not underpinned by appropriate skills and capacity – carries significant social, economic and environmental risks and may lead to missed opportunities. Specifically, in developing countries the deployment and implementation of best cooling practices will require particular attention to skills and capacity building for the design, installation, commissioning, inspection, maintenance and disposal of cooling equipment, as well as the enabling, coordinating, implementing, financing, enforcing and evaluating of policies and programmes.

Meeting anticipated global cooling demand in line with climate and developmental goals requires significant improvements in the energy efficiency supported by Minimum Energy Performance Standards (MEPS) and limits on the GWP of refrigerants. The demand for the knowledge and skills required to successfully develop and adopt these new technologies will be manifest at multiple levels of education and training. While the skills required to design, manufacture, commercialise and market sustainable cooling solutions are high, training of technicians of various grades requires equal attention to ensure proper installation and servicing of next generation, more technically complex, data- and system-connected equipment with alternative refrigerants with low/ultra-low GWP.

Equally, existing installed low efficiency/high-GWP refrigerant cooling systems can see material improvements today in energy efficiency and environmental impact by proper installation and maintenance. Technical training across all levels should lead to better outcomes in the management of cooling loads, improved operation and maintenance of equipment to maintain optimum system performance and accurate verification of the performance of installed cooling assets.

In addition to closing the skill gaps at all technical levels and attracting new engineers and technicians into the sector, broader training is also needed to create a better prepared market for absorbing these new technologies and ensuring the associated economic, social and environmental benefits are realised. In this regard, continuous education and training provision is needed for all stakeholders, including project developers, contractors and end users, to raise awareness of the benefits of sustainable and resilient cooling access, facilitate behavioural change and increase the uptake of systems thinking, best-in-class technologies and best professional practice.

Recommendations

The impacts of a warmer world on industrial personnel, buildings and assets, such as equipment and plant, are complex and broad, including technical, socio-economic and health related. Industry, government policymakers, the engineering profession and academia need to come together and act collaboratively to ensure workers and assets are protected against future extreme heat events through adaptation and the building of capacity for resilience. The industries considered in this report underpin the economic well-being of people and nations in the developed and developing world alike. As such, it is vital that their integrity and productivity is maintained during heatwaves, as well as in an environment characterised by an overall increase in seasonal ambient temperatures.

Adapting to, and preparing for, a warmer world will be essential for the future successful functioning of industry and in this regard the Institution of Mechanical Engineers makes the following recommendations:

1. **Industry needs to recognise that in many countries of the world their personnel, buildings and physical assets will be increasingly impacted by higher ambient temperatures and severe long-duration heatwaves, potentially leading to industrial unrest, operational shutdowns and lower levels of economic productivity. To avoid such outcomes, organisations must develop and implement adaptation plans for people, buildings, equipment and plants and invest in increasing their capacity for resilience to extreme heat events. Courses of action should include:**
   - employers and employees, with guidance from relevant health and safety bodies, such as the HSE in the UK, co-designing strategies for dealing with heat stress which are tailored to the specific needs of the different categories of workers and their workplaces. This may include setting a meaningful upper temperature, but the specifics will vary from industry to industry as working conditions, level of PPE and work-load are sector-dependent.
   - senior managers creating an enabling environment in which their engineering and operational teams can develop innovative and timely adaptation solutions for equipment, plant and buildings.
   - managers encouraging engineers to engage with national and international standards writing bodies in the updating of existing standards and design codes to account for higher temperatures and more frequent heat extremes, as well as developing new ones for adaptation and resilience more broadly.
   - organisations implementing 'build back better', rather than 'like for like', approaches to replacing aged or damaged buildings and assets to ensure that they are fit for future service in a hotter world.

2. **Government policymakers around the world need to recognise the potential productivity impacts of higher ambient temperatures and heat extremes on industries that underpin their national and local economic well-being and support them to adapt by:**
   - raising awareness of the projected heat-related impacts of climate change on industrial assets and buildings and encourage owners, developers, financiers, lenders and those involved in their design and construction to take urgent action on adaptation.
   - ensuring planning policy includes the evaluation of, and changes to, existing planning requirements for new builds and retrofits to reduce exposure to climate change-induced heat impacts.
   - reviewing and updating building codes and regulations to ensure they are relevant to future higher ambient temperatures and more frequent and severe heatwaves of longer duration.
   - ensuring that national net-zero strategies and investment decisions address the threat from higher ambient temperatures and extreme heat events to the performance of the technologies and industries upon which they are based.

- developing an energy policy vision for industrial cooling that is not constrained by defaulting to electricity, but instead is based on the fact that its provision could often be better achieved by "thinking thermally" and utilising available thermal resources.
- encouraging high hazard industry regulators to mandate operator assessments of extreme heat risks alongside other climate threats within their license-to-operate application, as well as to carry out a gap analysis between original design specifications and more recent future climate data. Operators must determine thresholds beyond which operations are no longer sufficiently resilient and establish adaptation plans to create resilience.

3. **The engineering profession worldwide is central to achieving a society well adapted to future climate change and, in this regard, engineers need to help industry prepare for the potential impacts of increased temperatures by:**
   - offering their time and expertise to national and international standards writing bodies, to help accelerate the process of updating existing standards and design codes to account for future heat impacts, as well as develop new ones focused specifically on addressing aspects of adaptation and the building of capacity for resilience.
   - recognising that simply transferring design and operational practice from already hot countries to those that are getting warmer is not necessarily an adaptation solution, due to differences in economies (ie costs of energy, labour, materials, etc.), land-use and GHG emissions policies, and environmental and workplace regulations impacting on the viability of commercial business models.
   - devising, developing and implementing innovative adaptation solutions to future heat impacts on industrial assets and buildings that are based on the principles of net-zero emissions, sustainability and the circular economy.
   - taking a holistic system-of-systems level approach to developing industrial adaptation solutions in which there is consideration and prioritisation of critical interdependencies for establishing failure risk mitigation strategies.

4. **Academia and skills development bodies must recognise that current technical training and education provision for engineers was designed on the assumption of a climate-stable future, in which temperatures are like the recent past, and that there is now a need to:**
   - ensure that basic climate change knowledge is taught throughout all engineering disciplines at every level and curricula considers the impact of higher ambient temperatures and more severe heat extremes, as well as potential approaches to adaptation and the principles of sustainable net-zero design, the circular economy and resilience.
   - make engineering education and skills training more accessible, relevant, responsive and transformative to inspire, attract and retain an expanding and more diverse range of people with non-traditional academic profiles into the profession. Upskilling and continuous professional development also have an essential part to play in allowing greater talent mobility between businesses, academia and other organisations in both the public and private sectors.
   - equip engineers with the knowledge and skills necessary for working collaboratively, particularly in international collaborations.

Appendix – footnotes

A A heatwave is an extended period of hot weather relative to the expected conditions of the area at that time of year, which may be accompanied by high humidity. The exact definition of a heatwave occurrence varies from country to country. In the UK, the heatwave threshold is met when a location records a period of at least three consecutive days with daily maximum temperatures meeting or exceeding a county-based heatwave temperature threshold. **[Return to text]**

B On the basis of current policies and pledges, a 2.8°C outcome by 2100 is anticipated[5,6]. **[Return to text]**

C Net-zero refers to a state in which the greenhouse gases going into the atmosphere are balanced by removal from the atmosphere. Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered[7] **[Return to text]**

D A sink is anything, natural or otherwise, that accumulates and stores GHGs for an indefinite amount of time, removing them from the atmosphere. **[Return to text]**

E The IPCC express a level of confidence using five qualifiers: virtually certain 99–100% probability; very likely 90–100%; likely 66–100%; about as likely as not 33–66%; unlikely 0–33%; very unlikely 0–10%; and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%; more likely than not >50–100%; and extremely unlikely 0–5%) are also used when appropriate. Assessed likelihood is typeset in italics; for example, very likely. This is consistent with Assessment Report (AR5). **[Return to text]**

F The body reacts to heat by increasing blood flow to the surface of the skin and by sweating, then as the sweat evaporates the surface cools. However, heat stress can occur when this mechanism of controlling internal body temperature fails and the body cannot shed excess heat. Under such conditions, the body's heart rate increases and its core temperature rises, the person begins to find it difficult to concentrate, feels unwell, and may experience fainting. Ultimately death can result if the body is not cooled down. **[Return to text]**

G Predicted mean vote (PMV) is an index that aims to predict the mean value of votes of a group of occupants on the seven-point scale. In order to compute PMV, simulated temperature and airspeed velocity are used as environmental inputs, along with clothing insulation, relative humidity and mean radiative temperature. Predicted percentage dissatisfied (PPD) is an index that establishes a prediction of the percentage of occupants who are thermally dissatisfied, using the PMV. **[Return to text]**

H A warming world will increase the uptake of artificial cooling technologies, which in turn will increase GHG emissions, global warming and demand for cooling. **[Return to text]**

I The concept of a net-zero CO_2 emissions outcome for a given technology, system, sector or economy involves reducing GHG emissions as much as is possible for the particular case being addressed and then balancing any remaining (residual) emissions through the use of carbon offset accounting and/or direct removal of an equivalent amount of GHG from the atmosphere (commonly referred to as 'negative emissions' [78,79]). **[Return to text]**

J Passive cooling systems are those that use no energy, as opposed to active cooling systems that use energy for cooling. **[Return to text]**

K See section on 'Sustainable net-zero cooling in practice' for examples of such approaches and technologies. **[Return to text]**

L ‘Life cycle’ is not the same as ‘design life’ – indeed, engineers have maintained railway assets that are approaching 200 years of age, which were never designed with a ‘design life’ in mind but have been kept safe and operational through good asset management practices. One perspective is that ‘design life’ as a concept works well for fatigue, or wear and tear, but is not necessarily a helpful concept in areas of large uncertainty such as exist when projecting the future climate and its associated hazards. **[Return to text]**

M Transformational adaptation is different to incremental adaptation in that it involves a system wide change or changes across more than one system and direct questioning of the effectiveness of existing systems, social injustices and power imbalances. **[Return to text]**

N In 1990, the Technology and Economic Assessment Panel (TEAP) was established as the technology and economics advisory body to the Montreal Protocol Parties. **[Return to text]**

O In April 2021, Gree Electric Appliances, Inc. of Zhuhai with partner Tsinghua University, and Daikin with partner Nikken Sekkei Ltd., emerged as the two winners of the Global Cooling Prize among eight finalists, by producing prototypes that exceed the Global Cooling Prize’s 5X lower climate impact criteria[102]. **[Return to text]**

P When using nature-based and passive solutions, such as predominant breezes, natural ventilation, tree shading, bodies of water, etc., consideration must be made of the future impacts on their cooling performance in a world where climates are changing because of, for example, wind pattern changes, increased air and water ambient temperatures, algae bloom in warmer waters, increased frequency and intensity of droughts and fluvial flooding events, tree stress mortality due to changes in atmospheric vapour pressure deficits and increased threats from pests and pathogens. **[Return to text]**

Q When using such nature-based ‘free’ cooling resources consideration must be made of the future impacts on their cooling performance in a world where climates are changing. For example, because of increased water ambient temperatures and the frequency and intensity of droughts, fluvial and coastal flooding events, as well as algae bloom in warmer waters and surface water and groundwater salination due to sea level rise. **[Return to text]**

References

1 The CAT Thermometer, Climate Action Tracker, November 2022. Available at: https://climateactiontracker.org/global/cat-thermometer

2 IMechE, Rising Seas: The Engineering Challenge. Institution of Mechanical Engineers, London, 2019. Available at: https://www.imeche.org/policy-and-press/reports/detail/rising-seas-the-engineering-challenge

3 Siegert, M., Alley, R.B., Rignot, E., Englander, J. and Corell, R., Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. One Earth 3, 2020, doi.org/10.1016/j.oneear.2020.11.002

4 https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

5 UNEP, The Closing Window, Emissions Gap Report 2022, United Nations Environment Programme, 2022. Available at: https://www.unep.org/resources/emissions-gap-report-2022

6 https://www.bbc.co.uk/news/science-environment-63407459

7 IPCC, Climate Change 2021: The Physical Science Basis, Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change), 2021. Available at: https://www.ipcc.ch/report/ar6/wg1/.

8 https://www.youtube.com/watch?v=LEUAp_u9FfY

9 https://www.who.int/europe/news/item/07-11-2022-statement---climate-change-is-already-killing-us--but-strong-action-now-can-prevent-more-deaths

10 IPCC, Climate Change 2022: Impacts, Adaptation, and Vulnerability. Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change, 2022, doi:10.1017/9781009325844.

11 https://www.clientearth.org/latest/latest-updates/stories/why-do-we-need-natural-carbon-sinks/

12 Allen, M.R., Dube, O.P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys S., Kainuma, M., Kala, J., Mahowald, N., Mulugetta, Y., Perez, R., Wairiu, M. and Zickfeld K., Framing and Context In Global Warming of 1.5ºC, An IPCC Special Report on the impacts of global warming of 1.5ºC above pre-industrial levels and related global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty. Cambridge University Press, 2018, doi:10.1017/9781009157940.003

13 https://www.eea.europa.eu/ims/global-and-european-temperatures

14 Met Office, UK Climate Projections: Headline Findings, August 2022. Met Office, 2022. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18_headline_findings_v4_aug22.pdf

15 https://www.bbc.co.uk/news/uk-64173485

16 https://blog.metoffice.gov.uk/2022/03/10/climate-change-and-extreme-events/

17 Pidcock, R. and McSweeney, R., Mapped: How climate change affects extreme weather around the world, Carbon Brief, August 2022. Available at: https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/

18 Founda, D., Katavoutas, G., Pierros, F. and Mihalopoulos, M., The Extreme Heat Wave of Summer 2021 in Athens (Greece): Cumulative Heat and Exposure to Heat Stress, Sustainability, 14(13), 2022, https://doi.org/10.3390/su14137766

19 https://www.worldweatherattribution.org/western-north-american-extreme-heat-virtually-impossible-without-human-caused-climate-change/

20 https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2022/driest-july-in-england-since-1935

21 https://multimedia.scmp.com/infographics/news/china/article/3190803/china-drought/index.html

22 https://www.weforum.org/agenda/2022/08/china-factories-drought-electricity-climate-change/

23 Gallus, W., What is a heat dome?, World Economic Forum, June 2022. Available at: https://theconversation.com/what-is-a-heat-dome-an-atmospheric-scientist-explains-the-weather-phenomenon-baking-california-and-the-west-185569

24 Thompson, V., Kennedy-Asser, A. T., Vosper, E., Lo, Y. T. E., Huntingford, C., Andrews, O., Collins, M., Hegerl, G. C. and Mitchell, D., The 2021 western North America heat wave among the most extreme events ever recorded globally, Sci. Adv., 8(18), 2022, doi:10.1126/sciadv.abm6860

25 https://www.reuters.com/world/uk/luton-airport-runway-meltdown-shows-airports-vulnerable-climate-change-2022-07-22/

26 https://theconversation.com/why-uk-railways-cant-deal-with-heatwaves-and-what-might-help-187311

27 https://www.express.co.uk/news/science/1640515/energy-crisis-heatwave-prices-rise-higher-price-cap-update

28 https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

29 Sulikowska, A. and Wypych, A., Summer temperature extremes in Europe: how does the definition affect the results?, Theoretical and Appliet Climatology,141(1-2), 2020.

30 Working on a warmer planet: The impact of heat stress on labor productivity and decent work, International Labor Organisation, Geneva, 2019.

31 Harari, D., Productivity: Key Economic Indicators, House of Commons Library: Research Briefing, 2022.

32 https://www.osha.gov/heat-exposure/hazards

33 Public Health England, Alert Reference, CEM/CMO/2020/027. Available at: https://www.cas.mhra.gov.uk/ViewandAcknowledgment/ViewAttachment.aspx?Attachment_id=103597

34 ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy, 2020

35 https://www.hse.gov.uk/temperature/thermal/

36 Health and Safety Executive: Workplace (Health, Safety and Welfare) Regulations 1992. Approved Code of Practice and Guidance, 2013

37 ISO, ISO 7730:2005, Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, International Organization for Standardisation, 2005. Available at: https://www.iso.org/standard/39155.html

38 https://danieloverbey.blogspot.com/2013/02/evaluating-human-thermal-comfort.html

39 https://www.reuters.com/article/uk-soccer-temperature-idUKKBN1W511S

40 https://www.osha.gov/heat-exposure/hazards

41 Coffel, E. D., Horton, R. M. and de Sherbinin, A., Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century, Environmental Research Letters, 12(1), , 2018, doi:10.1088/1748-9326/aaa00e

42 BP U.S. Pipelines and Logistics (USPL) Safety Manual: Heat Stress, November 2021. Available at: https://www.bp.com/content/dam/bp/country-sites/en_us/united-states/home/documents/products-and-services/pipelines/contractor-information/policy/heat-stress-policy.pdf

43 UNDP, Climate Change and Labour: Impacts of Heat in the Workplace. Occupational Health Risks, and Productivity—An Emerging Global Challenge to Decent Work, Sustainable Development and Social Equity, 2016. Available at: https://www.undp.org/publications/climate-change-and-labor-impacts-heat-workplace

44 Jha, R., Extreme Heat Events in India's Cities: A Framework for Adaptive Action Plans. Observer Research Foundation Issue Brief No. 437. Observer Research Foundation, 2021.

45 https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health

46 Vicedo-Cabrera, A.M., Scovronick, N., Sera, F. et al., The burden of heat-related mortality attributable to recent human-induced climate change, Nature Climate Change, 11, 2021.

47 Health and Safety Executive, The Workplace (Heath, Safety and Welfare) Regulations 1992, Regulation 22.

48 Cruz, J., White, P. C. L., Bell, A. and Coventry, P. A., Effect of Extreme Weather Events on Mental Health: A Narrative Synthesis and Meta-Analysis for the UK, Int. J. Environ Res Public Health, 17(22), 2020.

49 https://www.theguardian.com/environment/2021/may/26/climate-crisis-inflicting-huge-hidden-costs-mental-health

50 Hajat, S., O'Connor, M. and Kosatsky, T., Health effects of hot weather: from awareness of risk factors to effective health protection. The Lancet, 375(9717), 2010.

51 http://www.ibc.ca/bc/resources/media-centre/media-releases/insured-losses-in-lytton-bc-increase-to-102-million

52 https://www.cia.org.uk/About-us/Our-industry

53 https://www.npr.org/2018/07/27/632988813/hot-weather-spells-trouble-for-nuclear-power-plants

54 UK Climate Risk, UK Climate Risk Independent Assessment (CCRA3), Technical Report, 2021. Available at: https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/

55 Ian Gibbard, Therco-Serck Ltd.

56 https://www.peyto.com

57 https://www.peyto.com/Files/PMReport/2021/PMRJul42021_b.pdf

58 https://www.metoffice.gov.uk/research/climate/understanding-climate/uk-and-global-extreme-events-heatwaves

59 BEIS, The Non-Domestic National Energy Efficiency Data-Framework (ND-NEED) 2020 (England and Wales), Department for Business, Energy and Industrial Strategy (BEIS), UK Government, London 2020. Available at: https://www.gov.uk/government/collections/non-domestic-national-energy-efficiency-data-framework-nd-need

60 https://www.bbc.co.uk/news/world-48395221

61 Borg, M.A., Xiang, J., Anikeeva, O., Pisaniello, D., Hansen, A., Zander, K., Dear, K., Sim, M.R. and Bi, P., Occupational heat stress and economic burden: A review of global evidence, Environmental Research, 195, 2021.

62 https://grist.org/extreme-weather/europe-heat-wave-energy-crisis-cost/

63 https://www.lifeiris.eu/en/

64 CEN/CENELEC, Tailored Guidance for Standardization Technical Committees: How to include adaptation to climate change (ACC) in European Infrastructure Standards, CEN/CENELEC, 2022. Available at: https://boss.cen.eu/media/BOSS%20CEN/ref/climate_adpatation_in_standards_guidance.pdf

65 SCC, Guide for Integrating Climate Change Adaptation Considerations into Canadian Standards, Version 1.0, Standards Council of Canada, 2021. Available at: https://www.scc.ca/en/system/files/publications/SCC_Climate_Change_Guide_EN.pdf

66 https://eurocodes.jrc.ec.europa.eu/en-eurocodes/eurocodes-family

67 https://standards.iteh.ai/catalog/standards/cen/e24fc1d0-d8bd-4274-a3fc-125220f008e4/en-1991-1-5-2003

68 ASHRAE, ASHRAE Handbook – Fundamentals, ASHREA, 2021. Available at: https://www.ashrae.org/technical-resources/ashrae-handbook/description-2021-ashrae-handbook-fundamentals

69 CIBSE, Guide A: Environmental Design (2015, updated 2021), CIBSE, 2015, Available at: https://www.cibse.org/knowledge-research/knowledge-portal/guide-a-environmental-design-2015

70 CIBSE, TM52 The Limits of Thermal Comfort: Avoiding Overheating in European Buildings, CIBSE, 2013. Available at: https://www.cibse.org/knowledge-research/knowledge-portal/tm52-the-limits-of-thermal-comfort-avoiding-overheating-in-european-buildings

71 https://www.cibse.org/weatherdata

72 https://www.gov.uk/government/publications/adapting-to-climate-change-uk-climate-projections-2009

73 https://energyplus.net/weather

74 Morris, R., Guide on Future Climatic Data for Structural Design of Buildings, National Research Council Canada, 2021.

75 Cannon, A.J., Jeong, D.I., Zhang, X. and Zwiers, F.W., Climate-Resilient Buildings and Core Public Infrastructure: An Assessment of the Impact of Climate Change on Climatic Design Data in Canada, Government of Canada, Ottawa, 2020. Available at: https://climate-scenarios.canada.ca/?page=buildings-report-overview

76 https://k-cep.org/wp-content/uploads/2018/03/Optimization-Monitoring-Maintenance-of-Cooling-Technology-v2-subhead....pdf

77 Peters, T., A Cool World: Defining the Energy Conundrum of Cooling for All, University of Birmingham, 2018. Available at: https://www.birmingham.ac.uk/Documents/college-eps/energy/Publications/2018-clean-cold-report.pdf

78 IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change, 2014. Available at: https://www.ipcc.ch/report/ar5/syr/

79 Committee on Climate Change, Net Zero The UK's contribution to stopping global warming, Climate Change Committee, UK, 2019. Available at: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

80 UNEP, Cooling Emissions and Policy Synthesis Report, UN Environment Programme, 2020. Available at: http://www.unep.org/resources/report/cooling-emissions-and-policy-synthesis-report

81 GIZ, Coordinating finance for sustainable refrigeration and air conditioning, GIZ, Eschborn, Germany, 2018. Available at: https://www.green-cooling-initiative.org/fileadmin/Publications/2018_09_Coordinating_finance_for_sustainable_RAC.pdf

82 https://www.linkedin.com/pulse/adaptation-needs-net-zero-too-dr-tim-fox-1e/?trackingId=O%2FwQ%2FyTs4EsKmz4dGYNYOA%3D%3D

83 http://theconversation.com/climate-scientists-concept-of-net-zero-is-a-dangerous-trap-157368

84 Meckling, J. and Biber, E., A policy roadmap for negative emissions using direct air capture, Nature Communications, Vol. 12, 2021, doi: 10.1038/s41467-021-22347-1.

85 https://sdgs.un.org/goals

86 IMechE, A Tank of Cold: Cleantech Leapfrog to a More Food Secure World, Institution of Mechanical Engineers, London, 2014. Available at: https://www.imeche.org/docs/default-source/1-oscar/reports-policy-statements-and-documents/a-tank-of-cold---cleantech-leapfrog-to-a-more-food-secure-world.pdf?sfvrsn=7aece12_0

87 Birmingham Energy Institute, Doing Cold Smarter, University of Birmingham, 2014. Available at: https://www.birmingham.ac.uk/Documents/college-eps/energy/policy/Doing-Cold-Smarter-Report.pdf

88 https://soundcloud.com/user-918149949/business-model-innovations-addressing-affordability

89 https://www.carbonbrief.org/climate-change-made-2022s-uk-heatwave-at-least-10-times-more-likely/

90 ISO, ISO 14090:2019, Adaptation to Climate Change – Principles, requirements and guidelines, International Organization for Standardization, 2019. Available at: https://www.iso.org/standard/68507.html

91 ISO, ISO 14091:2021, Adaptation to Climate Change – Guidelines on vulnerability, impacts and risk assessments, International Organization for Standardization, 2021. Available at: https://www.iso.org/standard/68508.html

92 https://safety.networkrail.co.uk/wp-content/uploads/2017/02/NR-WRCCA-Strategy-2017-2019.pdf

93 https://www.metoffice.gov.uk/research/approach/collaboration/ukcp

94 https://climate-adapt.eea.europa.eu

95 BSI, BS8631:2021, Adaptation to Climate Change. Using adaptation pathways for decision making. Guide, British Standards Institution, 2021. Available at: https://knowledge.bsigroup.com/products/adaptation-to-climate-change-using-adaptation-pathways-for-decision-making-guide/standard

96 Singh, V.K., Bhati, S., Mohan, M., Sahoo, N.R. and Dash, S., Numerical simulation of the impact of urban canopies and anthropogenic emissions on heat island effect in an industrial area: A case study of Angul-Talcher region in India, Atmospheric Research, Vol 277, 2022, Available at: https://ui.adsabs.harvard.edu/abs/2022AtmRe.27706320S/abstract

97 https://www.drawdown.org/solutions/refrigerant-management

98 UNEP Ozone Secretariate, Fact Sheets on HFCs and Low GWP Alternatives, Fact Sheet 2: Overview of HFC Market Sectors, UN Environment Programme, 2015. Available at: https://ozone.unep.org/sites/ozone/files/Meeting_Documents/HFCs/FS_2_Overview_of_HFC_Markets_Oct_2015.pdf

99 https://ozone.unep.org/treaties/montreal-protocol

100 UNEP, TEAP Report, Volume 5: Decision XXIX/10 Task Force Report on issues related to energy efficiency while phasing down hydrofluorocarbons, Updated Final Report, UN Environment Programme, 2018. Available at: https://ozone.unep.org/sites/default/files/2019-04/TEAP_DecisionXXIX-10_Task_Force_EE_September2018.pdf

101 https://iaqa.org/consumer-resources/hvac-preventive-maintenance-is-essential/

102 https://globalcoolingprize.org/grand-winners-press-release/

103 https://globalcoolingprize.org

104 Peterson E. L., Appendix A S.4 Data associated with " Global and local bioclimatic predilections for rebalancing the heating and cooling of buildings", University of Leeds, 2022 [Dataset] https://doi.org/10.5518/967

105 https://www.me.iitb.ac.in/?q=individual-research-group%2FHeat+Pump+Laboratory

106 https://www.green-cooling-initiative.org/about-us/our-projects/proklima/2020/10/16/the-dumping-menace

107 https://www.imeche.org/news/news-article/the-energy-hierarchy-a-powerful-tool-for-sustainability

108 https://en.reset.org/new-smart-roofing-material-can-automatically-heat-or-cool-with-zero-emissions/

109 Gaoyuan Y., Yu, Z., Jorgensen, G. and Vejre, H., How can urban blue-green space be planned for climate adaption in high-latitude cities? A seasonal perspective. Sustainable Cities and Society, Vol 53, 2020.

110 Kesik, T., O'Brien, L. and Ozkan, A., Thermal Resilience Design Guide, Version 1.0, University of Toronto and ROCKWOOL North America, 2019. Available at: https://pbs.daniels.utoronto.ca/faculty/kesik_t/PBS/Kesik-Resources/Thermal-Resilience-Guide-v1.0-May2019.pdf

111 Maouris, G., Sarabia Escriva, E.J., Acha, S., Shah, N. and Markides, C.N., CO2 refrigeration system heat recovery and thermal storage modelling for space heating provision in supermarkets: An integrated approach, Applied Energy, vol. 264, 2020, doi: 10.1016/j.apenergy.2020.114722

112 GOV.UK, Clean growth – Transforming heating, overview of current evidence, UK Government, 2018. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/766109/decarbonising-heating.pdf

113 GOV.UK, Spring Statement 2019: what you need to know, UK Government, 2019. Available at: https://www.gov.uk/government/news/spring-statement-2019-what-you-need-to-know

114 Birmingham Energy Institute, The prospects for liquid air cold chains in India, University of Birmingham, 2014. Available at: https://www.birmingham.ac.uk/Documents/news/The-prospects-for-liquid-air-cold-chains-in-India.pdf

115 TechEmerge, LNG Waste Cold, Webinar Series, International Finance Corporation (IFC), 2021. Available at: https://www.techemerge.org/events/webinar-series-lng-waste-cold/

116 Romero Gómez, M., Ferreiro Garcia, R., Romero Gómez, J. and Carbia Carril, J., Review of thermal cycles exploiting the exergy of liquefied natural gas in the regasification process', Renewable and Sustainable Energy Reviews, vol. 38, 2014, doi: 10.1016/j.rser.2014.07.029

117 Badami, M., Bruno, J.C., Coronas, A. and Fambri, G., Analysis of different combined cycles and working fluids for LNG exergy recovery during regasification, Energy, vol. 159, 2018, doi: 10.1016/j.energy.2018.06.100

118 https://www.enagas.es/en/press-room/news-room/press-releases/2019_10_10_NP_Shaky/

119 IMechE, The Future of International Collaborative Engineering. Institution of Mechanical Engineers, London, 2022. Available at: https://www.imeche.org/policy-and-press/reports/detail/the-future-of-international-collaborative-engineering

120 BEIS, UK Innovation Strategy: Leading the future by creating it, Department for Business, Energy and Industrial Strategy (BEIS), UK Government, 2021. Available at: https://www.gov.uk/government/publications/uk-innovation-strategy-leading-the-future-by-creating-it

Image credits: Cover/01: istock.com/Алексей Филатов; 02: istock.com/Bim; 06: istock.com/Viorika; 08: istock.com/querbeet; 10: istock.com/naveebird; 16: Associated Press; 24: istock.com/Chun Han; 44: istockcom/primeimages; 50: istock.com/Suphanat Khumsap; 54: istock.com/gorodenkoff

Institution of
Mechanical Engineers

1 Birdcage Walk
Westminster
London SW1H 9JJ

+44 (0)20 7973 1293
media@imeche.org
imeche.org