ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Climate change risk trap: low-carbon spatial restructuring and disaster risk in petroleum-based economies

To cite this article: Viktor Rözer *et al* 2025 *Environ. Res. Lett.* **20** 024052

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Climate change risk trap: low-carbon spatial restructuring and disaster risk in petroleum-based economies

OPEN ACCESS

RECEIVED
30 June 2024

REVISED
2 December 2024

ACCEPTED FOR PUBLICATION
22 January 2025

PUBLISHED
4 February 2025

Viktor Rözer[1,*], **Sara Mehryar**[2] **and Mohammad M M Alsahli**[3]

[1] Centre for Integrated Research in Risk and Resilience (CIRRR), Department of Geography, King's College London, Strand, London WC2R 2LS, United Kingdom
[2] Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, Houghton Street, London WC2A 2AE, United Kingdom
[3] Department of Geography, College of Social Sciences, Kuwait University, PO Box 5969 Kuwait, Safat 13060, Kuwait
[*] Author to whom any correspondence should be addressed.

E-mail: viktor.roezer@kcl.ac.uk

Keywords: climate change, disaster risk, coupled systems, green transition

Abstract

The economic risks from climate change can be separated into two categories: physical risks from increased frequency and magnitude of extreme weather and climate events, and transition risks due to rapid decarbonisation leading to stranded assets and shifts in production and the labour market. On the global level, the two risks are widely recognized as trade-offs by the academic and policy literature: rapid decarbonisation increases transition risks while reducing physical risks, and vice versa for a delayed reduction of greenhouse gas emissions. In contrast, little is known about the interaction between the two risks on smaller geographical scales. This paper investigates the interactions between physical and transition risks on the sub-national level for petroleum-based economies. Their strong dependency on the export of fossil fuels requires a more far-reaching economic restructuring to meet both local and global emission targets than most other economies, exposing them to high transition risks. At the same time, the profound economic changes resulting from a low-carbon transition lead to a spatial redistribution of assets and labour, when brown assets and jobs get stranded and new green assets and jobs are created elsewhere. Building on the literature on spatial economic restructuring and climate disaster risk, we show that, unlike the common conceptualisation as a trade-off, physical and transition risk can increase simultaneously on the sub-national level. We call this dynamic the climate change risk trap. The paper provides an empirical illustration of this trap using the example of flash flood risk in Kuwait, a wealthy petroleum-based economy in the Gulf region. It shows how decisions on urban planning and low-carbon economic restructuring have increased flash flood risk. The analysis highlights the importance of considering climate disaster risk and environmental impact assessments in low-carbon transition planning to avoid falling into the climate change risk trap.

1. Introduction

The fight against climate change will lead to far-reaching changes across the world (Foxon 2011, Niamir *et al* 2018). In countries with high greenhouse gas (GHG) emissions, a large part of these changes originate in the need to decarbonise their economies to prevent a destabilization of the earth's climate (Hitz and Smith 2004, Rockström *et al* 2009) while bracing for more frequent extreme weather events and sea level rise as a result of the climate change already underway (Stott 2016, Griggs and Reguero 2021).

The risks associated with decarbonisation on one side and losses and damages from extreme weather and climate events on the other are referred to as transition and physical risks in the economic and financial climate change risk literature (Batten *et al* 2016, Carattini *et al* 2023).

Transition risks describe the uncertainty around the economic and financial impacts of shifting to a low-carbon or 'green' economy including changes to the labour market, technology and assets. Transition risks are considered higher the more rapid and extensive economies need to be restructured to meet internationally agreed GHG emission reduction targets (McGlade and Ekins 2015, Batten 2018). Physical risks, on the other hand, describe the increased probability of direct impacts of climate change in the shape of losses and damages to humans as well as the natural and built environment from acute (extreme weather) and chronic (sea level rise, droughts) climate events (Dietz *et al* 2016).

On the global level, Lenton and Ciscar (2013) and TCFD (2017) have conceptualized the relationship between transition risk and physical risk as a trade-off: fast and ambitious decarbonisation of the world economy bears high transition risks, due to a higher probability of social and economic disruptions. At the same time physical risks are reduced as faster reductions in GHG emissions lower the likelihood of escalating direct impacts from extreme weather and climate events. Contrary, a slow transition requires less drastic steps to restructure economies and societies but will lead to higher GHG emissions and consequently to higher physical risks due to higher costs for adaptation and from losses and damages.

While the concept of climate risk as a trade-off between physical and transition risk is compelling on the global scale, how these two risks interact on the national and sub-national level is not well understood. This presents a challenge for climate change adaptation (CCA) and mitigation planning, which is primarily decided on those lower levels. The main reason for this knowledge gap is that transition and physical risks are usually analysed separately, especially on the local level. Recent studies looking at transition risks from climate change on the sub-national level, have emphasized the spatial dimension of the risks from economic restructuring as part of a countries 'green transition' (While *et al* 2010, Garvey *et al* 2022, While and Eadson 2022). These studies utilise the literature on economic restructuring from the 1980s and 1990s to look at the 'spatial divisions' that are created through the redistribution of economic opportunities and adversities within a country or region by having to 'strand' assets and jobs, directly or indirectly linked to fossil fuels in one place, while new 'green' assets and employment, required for the low-carbon economy, are created elsewhere (Kennedy and Corfee-Morlot 2013, Pan 2014, Ioannidou *et al* 2020, Van der Ploeg and Rezai 2020, Semieniuk *et al* 2022). We refer to this framework as 'low-carbon (or green) spatial economic restructuring. While many decisions on low-carbon spatial economic restructuring are made top–down through national or transnational industrial policies, the impacts on transition and physical risk primarily play out locally (Zachmann 2022). However, local interactions of transition risks from 'spatial economic restructuring' with the physical risks from climate change are usually ignored in these studies, as it is currently difficult to attribute changes in the local frequency and severity of extreme weather and climate events to individual efforts to lower GHG emissions (Doblas-Reyes *et al* 2021). On the other side, physical risk is primarily understood as climate-related disaster risk on the local level, where only the hazard (i.e. extreme weather and climate events) is linked to the transition risks by considering (global) increases in GHG emissions (see for example Bates *et al* 2023). Other drivers of physical risks such as exposure and vulnerability to extreme weather and climate events are usually seen as independent from or only indirectly influenced by the transition to a 'green' or low-carbon economy through generalized trends such as population growth or land-use changes (Field *et al* 2012).

This paper addresses this research gap on the interaction between physical and transition risks on the local level in two ways. First, by combining the literatures on low-carbon spatial economic restructuring (While and Eadson 2022) and climate-related disaster risk (Field *et al* 2012) in a new framework describing the interactions between physical and transition risk on the national to local scale. Second, by applying this new framework to empirically analyse those interactions for local case study of a petroleum-based economy.

We focus our research on petroleum-based economies, using the example of Kuwait, due to their unique role as the world's largest indirect contributors to physical risks from climate change through upstream GHG emissions, while at the same time facing one of the highest economic and financial risks from the low-carbon transition (Bang and Lahn 2020).

By disentangling climate-related disaster risk into its three components—hazard, vulnerability, and exposure—we analyse how low-carbon spatial economic restructuring influences both physical and transition risks locally and how it shapes the overall risk from climate change of petrol-based economies (i.e. the sum of physical and transition risks over time) (Simpson *et al* 2021). We discuss that other than the trade-off on the global level, the interaction between physical and transition risk on the national and sub-national level depends on the ability to spatially organise low-carbon economic restructuring in a way that does not significantly increase the exposure and vulnerability of people and assets to physical hazards such as floods, heat or drought.

For cases where the overall climate change risk increases due to growing exposure and vulnerability from low-carbon economic restructuring, we coin the term *climate change risk trap*. We illustrate this *climate change risk trap* for the example of Kuwait, a wealthy petroleum-based economy and one of the largest global exporters of petroleum products.

Based on empirical data of Kuwait's urban development since the discovery of oil in the 1950s as well as Kuwait's urban development plan up to the 2040s in combination with existing evidence on climate change impacts, we demonstrate how the transition to a low carbon economy drives the creation of new assets and people vulnerable and exposed to the physical effects of climate change.

2. Background and setting

Actions to reduce the negative impacts of climate change can be distinguished between climate change mitigation, which describes actions to limit global warming by GHG emissions, and adaptation, which aims to reduce the negative consequences of climate change to humans and the environment by reducing their exposure and vulnerability to impacts such as extreme weather events (Klein *et al* 2007). Especially in developed and emerging economies with high GHG emissions, CCA and mitigation need to be integrated to meet internationally agreed targets on both emissions under the Paris Agreement and disaster risk reduction under the Sendai Framework (Lesnikowski *et al* 2017, Hurlimann *et al* 2021, Howarth and Robinson 2024). However, mitigation and adaptation targets are often in conflict with each other or come with significant trade-offs (Sharifi 2020). These conflicts and trade-offs depend on several factors including changing infrastructure (Kennedy and Corfee-Morlot 2013, Fisch-Romito and Guivarch 2019) and labour demand (García-García *et al* 2020) in a low-carbon economy. They also depend on the availability of geographical locations for new developments that are both suitable and safe from climate-related hazards (Marin and Modica 2017).

Several studies have looked at these factors individually, such as the vulnerability to climate-related hazards of low-carbon built assets such as low-energy houses (Balasbaneh *et al* 2019) or wind farms (Zhang *et al* 2019). Hanson and Nicholls (2020) analyse future risks of ports in response to the combined changes in sea-level rise and trade patterns in a low-carbon economy. For the labour market, review studies often find an increase in net employment through a shift to a low-carbon economy, which can result in a higher number of people exposed to the impacts of climate change (Marin and Modica 2017, García-García *et al* 2020). A study on coal miners in Poland finds that 50% of coal miners could not find a job in another sector and left the labour market, while new workers came in for the green jobs that were created, resulting in a net increase in population in the region (Baran *et al* 2020).

Petroleum-based economies are particularly affected by the low-carbon transition. To be in line with the Paris Agreement's 2 °C objective more than 80% of the proven global fossil fuel reserves need to remain in the ground (Bos and Gupta 2019). With 38% of their known oil and 61% of their gas reserves, petroleum economies of the Gulf region have the highest share of fossil fuel resources that would need to be stranded under the Paris Agreement (McGlade and Ekins 2015).

All of the proposed visions for the future of petroleum-based economies of the Gulf region, including climate tech, tourism and green energy, require a far-reaching economic restructuring, including changes to the built environment, immigration of skilled labour and increasing energy demand (Thiollet 2016, Ansari and Holz 2020).

The combination of more frequent and intense extreme weather events and growing demand for housing and other built assets due to spatial low-carbon economic restructuring is likely to increase climate-related disaster risk in the region. Future sea level rise is threatening residential areas along the urbanised coastline (Alsahli and AlHasem 2016, Hassan and Hassaan 2020), several extreme rainfall events in recent years have caused significant damage (Al-Nakib 2016, Hassan *et al* 2024) and heat-related mortality in the Gulf region is projected to increase significantly by 2100 (Alahmad *et al* 2022). Building on the theoretical work by Lazarus (2022) on the disaster trap and the research & development trap (Arman *et al* 2022), we conceptually and empirically explore local interactions between physical and transition risks from climate change in petroleum-based economies in the Gulf region. For our empirical analysis, we analyse the past and future development of the two main climate-related risks in Kuwait: flash floods and extreme heat. To the best of our knowledge, this marks the first comprehensive longitudinal study of the local interactions between physical and transition risks in a petroleum-based economy of the Gulf region from the discovery of oil in the 1950s to the future plans for low-carbon economic restructuring up to 2040, taking into account the dynamic and rapidly changing demand for labour and housing.

3. The climate change risk trap

Disaster risk from climate change is shaped by hazard (i.e. weather and climate events), exposure and vulnerability (Field *et al* 2012). The future disaster risk from climate change depends on the intensity and frequency of extreme weather and climate events and is a function of natural variability and anthropogenic climate change. Failing to decarbonise and reduce GHG emissions leads to increasing impacts and costs from extreme weather and climate events both in terms of losses and damages and increased spending on CCA

(Fankhauser 2010, Stott 2016, Seneviratne *et al* 2021). While areas with the highest current and cumulative GHG emissions do not necessarily geographically overlap with the areas that will see the highest increases in climate-related impacts (Tol *et al* 2004), countries of the Gulf region have both rapidly increasing per capita GHG emissions (surpassing those of for example the European Union) and are also warming significantly faster than other inhabited regions. This leads to an intensification of the water cycle and an increase in extreme events such as extreme heat, droughts and flash floods (Pal and Eltahir 2016, Zittis *et al* 2022). Gulf region countries are also among the largest single contributors to upstream GHG emissions with oil and gas exported from the region being responsible for 8% of total cumulative GHG emissions between 1854 and 2010 (Heede 2014). We refer to this increase in climate change disaster risk by failing to reduce GHG emissions and the subsequent increase in extreme weather and climate events as the *delayed decarbonisation trap* (see figure 1—left side).

A fast and ambitious decarbonisation to meet globally agreed GHG emission reduction targets and to curtail a further increase in extreme weather and climate events requires stranding existing 'brown' assets and infrastructure linked to the oil and gas production and consumption while creating new 'green' assets and infrastructure for a decarbonised economy (McGlade and Ekins 2015, While and Eadson 2022).

Low carbon economic restructuring is driving change in three areas: population change through changing labour demands, land-use change by changing demand in built assets and infrastructure as well as fiscal changes by changing revenue streams to become independent from oil rents (Sim 2020, Mohammed *et al* 2022). These fundamental changes to a country's demographic, spatial and fiscal structure opens several channels for an increase in climate disaster risk through exposure and vulnerability.

The transition to a low-carbon economy can increase exposure through land use changes, with new assets and infrastructure being built in areas at risk (Bridge *et al* 2013, Tran and Egermann 2022). Exposure to extreme weather and climate events can also be driven by population growth due to labour immigration. Re-training the existing workforce is expected not to be sufficient to meet the labour demand of a low-carbon economy and is often compensated by immigration. The resulting increase in demand for housing can lead to a further increase in exposure to extreme climate and weather events (Müller *et al* 2013).

At the same time, fiscal stability decreases during the low-carbon transition, with public and private investors having to write off investments in sunset industries and facing an increased risk of bubbles in sunrise industries (Semieniuk *et al* 2021). With shrinking revenues from oil and gas, welfare spending cuts become more likely in order to maintain fiscal stability, increasing social vulnerability from increased inequality and poverty risks (Otto *et al* 2017). Due to the region's low domestic food production and water scarcity, revenues from oil and gas as well as cheap energy are deciding factors on how much fresh water and food can be produced locally and how much food can be imported (Siderius *et al* 2020). Reduced water and food security can directly or indirectly affect people's vulnerability and resilience to the impacts of extreme weather events (Tariq *et al* 2021).

Increasing climate disaster risk due to increasing exposure and vulnerability from low-carbon economic restructuring can make petroleum-based economies fall into the *low-carbon restructuring trap* (see figure 1—right side).

Chances of falling in either the *delayed decarbonisation trap* or the *low-carbon restructuring trap* depend on both global and local actions. Increases in extreme weather events and the subsequent risk of falling into the *delayed decarbonisation trap* due to the failed reduction of GHG gases is mainly driven by actions on the international level such as countries meeting agreed targets to limit global warming to 2 °C. However, as the world's largest exporters of oil and gas products, petroleum-based economies of the Gulf Cooperation Council (GCC) and elsewhere have additional leverage by leaving more of their known oil and gas reserves in the ground (Van de Graaf and Verbruggen 2015). In this context, Van de Graaf and Verbruggen (2015), Ansari and Holz (2020), and others discuss economic diversification as the most promising long-term strategy. However, this can affect the risk of a country falling into the *low-carbon restructuring trap*.

CCA can help reduce increases in disaster risk caused by both an increase in extreme weather and climate events and increasing exposure and/or vulnerability. However, CCA is subject to both physical (magnitude of extreme weather and climate events becoming too high) and economic (adaptation too costly under shrinking budgets) limits (Dow *et al* 2013).

We empirically illustrate this challenge for the example of Kuwait in the following section.

4. An empirical illustration of the climate change risk trap: flood risk in Kuwait

Based on the conceptual framework of the climate change risk trap outlined in figure 1 and described in section 3, we use a multi-method approach combining first and secondary data analyses to empirically illustrate the climate change risk trap for the example of Kuwait, a wealthy petroleum-based economy in the Gulf region. Figure 2 shows an illustration of the dynamics that put Kuwait's economy at

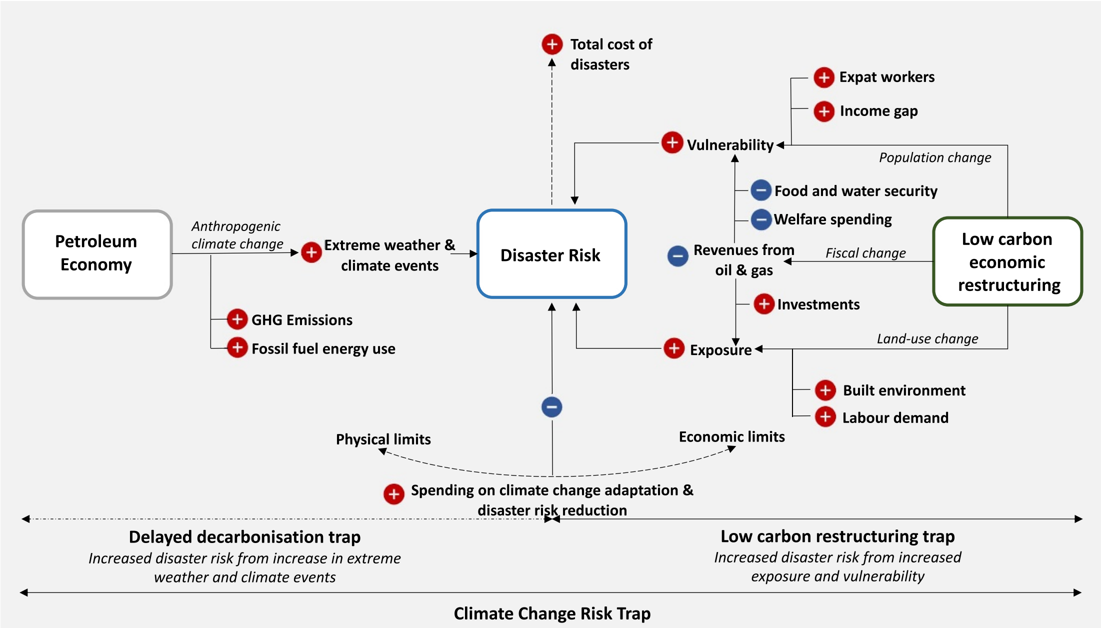

Figure 1. Framework to describe the climate change risk trap. The framework shows the interactions between low-carbon spatial economic restructuring on one side and unmitigated climate change on the other. It outlines the dynamic through which disaster risk in a region or country can still increase through an increase of exposure and vulnerability due to spatial low carbon restructuring ('*low-carbon restructuring trap*'). It also shows the more common dynamic through which disaster risk increases due to unmitigated climate change ('*delayed decarbonisation trap*'). Directed graphs show the direction of the dynamic while ('+': positive) and ('−': negative) indicate the direction of the trend.

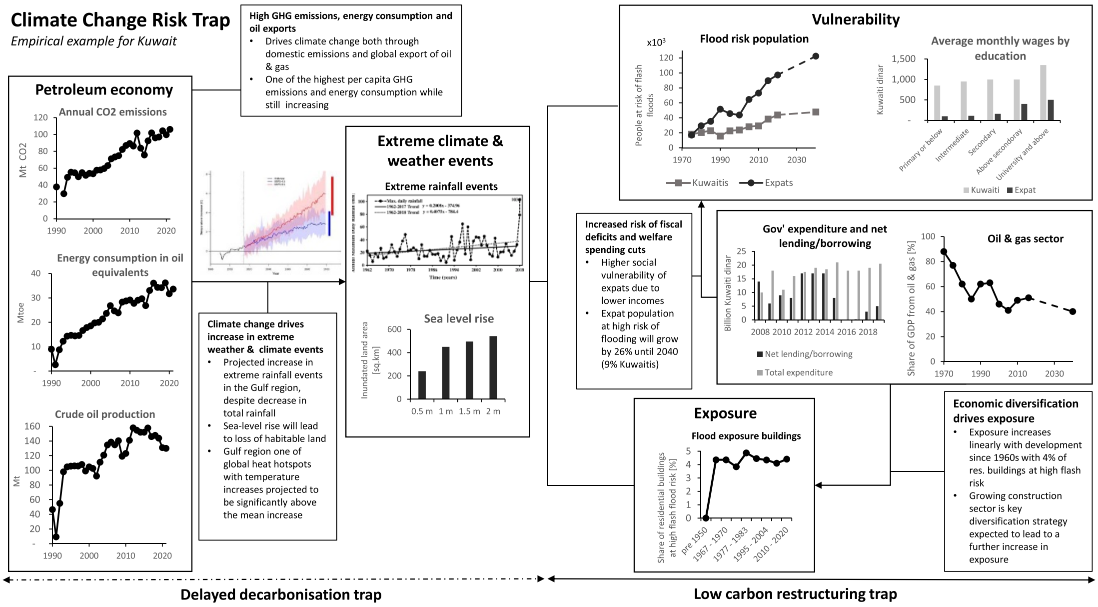

Figure 2. Empirical example of the climate change risk trap for Kuwait combining first and secondary data analyses. Sources for petroleum-based economy: Annual CO2 emissions Kuwait (Friedlingstein *et al* 2022), Kuwait energy consumption in oil equivalents and crude oil production (Enerdata 2023). Sources for extreme climate change, extreme weather and climate events: Kuwait increases in mean temperature until 2100 under SSP2-4.5 (blue) and SSP5-8.5 (red) (Alahmad *et al* 2022), extreme rainfall events in Kuwait (Al-Qallaf *et al* 2020) and sea level rise (Alsahli and AlHasem 2016). Sources for vulnerability: flood risk population (own analysis, appendix), average monthly wages by education (Hertog 2020). Sources for fiscal changes: government expenditure and net lending/borrowing (ibid) and share of GDP from oil and gas (Perkins and Will 2020). Sources for exposure (own analysis, appendix). The layout follows the conceptual model shown in figure 1. Text boxes describe the dynamics that drive the interaction between extreme weather and climate events, exposure and vulnerability for the low carbon economic restructuring of Kuwait's petroleum economy.

risk of falling into either the *delayed decarbonisation trap* or the *low carbon restructuring trap*. Details of our analysis, including a description of the methods used to develop the first flash flood hazard map for Kuwait and a longitudinal census micro data set can be found in the appendix.

Kuwait is a high-income city-state in the northeast of the Arabian Peninsula with a total population of 4.2 million (CIA 2024). With the discovery of oil and its international export from the 1950s, Kuwait underwent a large-scale transformation from a small Arab maritime town with only 150 000 inhabitants to a modern-day metropolis in just 70 years exceeding the growth rate of cities such as Shanghai or Mumbai (Al-Nakib 2016). The export of oil allowed Kuwait to transform and grow its economy with the desire to establish a modern welfare state sharing its newly acquired wealth with its population (Al-Nakib 2013, Hertog 2020). A focus area of the newly established welfare system was the provision of subsidized housing for citizens (Alshalfan 2013). From 1951 overseas consultancies and urban planners were commissioned to develop an urban planning vision for Kuwait in the shape of a master plan (Nilsson 2017). The first master plan aimed to transform the small town into a state-of-the-art and socially progressive city (Shiber 1964). The master plan largely followed Western urban planning principles and included the demolition of the historic old town of Kuwait to replace it with self-sufficient, low-density neighbourhoods separated by a radial road network with cars as the main mode of transportation (Alshalfan 2013). This planning approach not only showed early signs of being inadequate for the climatic conditions of the region due to its lack of protection from Sun, heat and sandstorms (Hewins 1963), it has also put Kuwait on a trajectory of urban sprawl with a resource intensive and car-centric society (Alkhuzamy Aziz and Alghais 2021). The rapid population growth of Kuwait since the 1950s, mainly driven by immigration to meet the growing demand for labour, accelerated the urban sprawl, while at the same time leading to segregation between migrant workers living in densely populated mixed-use areas and the Kuwaiti population mostly living in single-family units provided by the government (Alshalfan 2013). Modern-day Kuwait has reached a crossroads in its development. Its urban planning legacy is forcing Kuwait's residents into a carbon-intensive lifestyle through its car-centric transportation, high energy demand for cooling and drinking water production as well as an energy system solely relying on fossil fuels for energy generation (Alsayegh *et al* 2018). With 21 tonnes of CO2 per year, Kuwait currently has one of the highest per capita emissions globally and its total GHG emissions are still rising closely following its economic development (ClimateWatch 2023). This results in GHG emissions per GDP being almost twice above the OECD average (Al-Abdullah *et al* 2019). Despite plans to diversify its economy around 90% of Kuwait's revenues and half of its GDP are currently coming from oil rents, which is the highest share of all countries of the GCC (Alshalfan *et al* 2022). A recent drop in oil prices on the world market in 2018 led to an immediate contraction of Kuwait's economy by 5.6% underlining the continued high dependence on the oil sector (Gelan *et al* 2021). High volatility of oil revenues, in combination with high government spending for Kuwait's welfare system, which includes publicly financed housing, and subsidies for energy, water and food have pushed Kuwait into an unsustainable fiscal position (Hertog 2020, Gelan *et al* 2021). Kuwait's leaders have developed a plan for structural reforms to diversify its economy adressing both the high dependency on oil rents and high government expenditures on the public sector. Titled 'Kuwait 2035', the joint vision is to turn Kuwait into a regional and financial hub for the northern Gulf. Kuwait's economic diversification under this vision should mainly be achieved through the construction sector, with several infrastructure mega projects, including a new business hub, railway and metro systems, several new cities to house its growing population and additional basic infrastructure projects. To reduce the high government spending half of these investments are planned to come from the private sector (Olver-Ellis 2020).

At the same time, urban expansion and the construction of new housing have increased the exposure and vulnerability of its residents to climate-related extreme weather events and other environmental hazards such as air pollution (Al-Hemoud *et al* 2019). Over the last 5 years, Kuwait has suffered from two severe flash flood events with damages of several hundred million US$ (Hassan *et al* 2024). Analysing the flash flood exposure in the metro Kuwait area we find that between 1970 and 2020, the number of people living in areas with a flash flood risk (top 10% percentile) has quadrupled with currently around 140 000 people living in high-risk areas (see appendix). A considerably higher increase in flash flood risk was found for non-Kuwaitis, whose income is significantly and consistently lower compared to Kuwaitis through all education and income levels (Hertog 2020). This raises environmental justice questions and concerns about a growing social vulnerability to flooding, heat and other climate-related risks (Alahmad *et al* 2022, Alsahli and Al-Harbi 2022). Climate change will further increase the risk of flooding due to projected increases in extreme rainfall in Kuwait (Al-Qallaf *et al* 2020), leading to higher costs from losses and damages and investments in adaptation. Without significant global emission reductions including Kuwait's emissions, Neelamani *et al* (2022) estimated that sea level rise will lead to Kuwait losing land by 2100 currently worth USD193.8

billion. Heat-related mortality in Kuwait is projected to increase further under all climate scenarios by the 2050s (Alahmad *et al* 2022). Especially in the case of an extreme climate scenario (RCP 8.5), the risk of reaching wet-bulb temperatures in Kuwait that are above the threshold for survivability of a fit human (35 °C) is increasing considerably (Pal and Eltahir 2016). This increase in extreme weather and climate events as a result of failed climate change mitigation poses a real risk of Kuwait falling into a *delayed decarbonisation trap* with a continued increase in costs for adaptation and losses and damages from extreme weather and climate events as well as permanent loss of habitable land due to extreme heat, drought and sea level rise.

While the threat of escalating climate-related hazards on one side and concerns about fiscal stability due to a high dependency on volatile oil revenues on the other make economic diversification unavoidable, our analysis indicates a potential risk of falling into a *low-carbon economic restructuring trap*. Based on analysis of Kuwait's flash flood risk and population projections outlined in the fourth Kuwait master plan (Perkins and Will 2020), we find that even without the projected increase in extreme rainfall events an additional 30 000 people will be exposed to a high risk of flash flooding by 2040 with 89% being non-Kuwaitis with low wages and no access to the state welfare system. Analysing historic urban expansion patterns and their influence on flash flood risk, we find that Kuwait has so far failed to decouple its economic growth by increasing its exposure to extreme weather events such as floods. We find a similar trend for Kuwait's road infrastructure, which has been severely affected during the past two flash flood events (see appendix).

These metrics indicate the risk of a potential trap in which Kuwait's decarbonisation efforts increase the exposure and vulnerability to extreme weather and climate events. This leads to increased climate-related disaster risk in Kuwait even in cases where both local and global efforts to limit global warming are successful.

5. Discussion and conclusion

The paper illustrates the dual challenge many petroleum-based economies face with climate change. With their current and past economic development almost entirely based on the export of oil and gas, these countries are starting to prepare for a global decline in the demand for fossil fuels (Callen *et al* 2014). While the proposed plans for diversifying petroleum-based economies are as diverse as the individual challenges each country is facing (Mishrif 2018, Ansari and Holz 2020), there is a common pattern that includes spatial economic restructuring (While and Eadson 2022). We argue that the resulting demographic, fiscal and land-use changes can paradoxically increase a country's climate change disaster risk through an increase in exposure and vulnerability. This occurs despite successfully averting the most extreme climate and weather events through local and global GHG emission reductions over the coming decades. Using the first flash flood hazard map produced for the country, we empirically show for Kuwait, a major petroleum-based economy in the Gulf region, that its urban expansion over the past 70 years with new residential homes built in areas at risk of flooding has significantly contributed to the increase in flash flood risk. Current plans for spatial economic restructuring over the next two decades are expected to lead to a further increase in the flash flood risk in Kuwait. The increases in disaster risk driven by increases in exposure and vulnerability are already a common phenomenon (Winsemius *et al* 2016, Simpson *et al* 2021), and sector-specific or individual conflicts between climate change mitigation and adaption have previously been analysed (Sharifi 2020). However, the analytical concept of the climate change risk trap describes the systemic dilemma petroleum-based economies face due to the need to restructure their economies entirely. To avoid falling into either the *delayed decarbonisation* or the *low-carbon restructuring trap*, petroleum-based economies will have to manage their low-carbon economic restructuring carefully. They must reduce local and global GHG emissions without creating new risks by exposing vulnerable green assets and growing populations to climate-related hazards. The integration of environmental impact assessments as part of the planning process for the economic transition has been put forward by researchers to better understand the risks of new low-carbon spatial economic restructuring projects but has so far stayed behind its ambition (Al-Damkhi *et al* 2008). Given the projected demand for additional infrastructure and labour as part of the envisioned economic diversification as well as the long lifetime of many built assets, rapid action is required to avoid high additional investments in CCA measures over the coming decades. While our study provides the conceptual basis to understand the challenges and opportunities of low-carbon spatial economic restructuring of petroleum-based economies, future studies should focus on a full implementation of the concept, including the interaction between projected restructuring projects in combination with expected changes in extreme weather and climate events as a result of climate change. Our empirical analysis demonstrates the mechanism how plans to spatially re-structure petroleum-based economies, in an attempt to the break economic dependence from fossil fuels, can increase exposure and vulnerability to climate-related hazards, but other important factors such as demographic or political changes can have an equally large effect. To identify all channels that drive climate-related risks and empirically quantify the precises contribution of low-carbon economic restructuring more detailed causal inference studies are needed. Using the Gulf region as one of the world's largest producers of oil and gas as a case study, the results might not be transferable to petroleum-based economies where political instability, corruption and/or poverty is preventing any ambitious economic restructuring (Calverley and Anderson 2022).

Data availability statement

The data cannot be made publicly available upon publication due to legal restrictions preventing unrestricted public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This work was supported by the Kuwait Foundation for the Advancement of Science through the 'LSE Kuwait collaborative research program'. V R and S M acknowledge the support from the Grantham Foundation for the Protection of the Environment and the ESRC via the Centre for Climate Change Economics and Policy (ES/R009708/1).

The authors thank Mohammad R Alroomi and Anfal S Alenezi for their support in data collection. Thanks are also extended to Dalal Al Hashash from the Kuwait Foundation for the Advancement of Sciences (KFAS) for her logistical support during the project and Swenja Surminski for co-leading the project. Additionally, we acknowledge the Public Authority for Civil Information (PACI) for providing demographic data.

Appendix. Data and methods

A.1. Flash flood risk maps

A.1.1. Data

We integrated various geospatial data to map the flash flood risks on Kuwait's land surface. This includes ground control points (GCPs), Advanced Land Observing Satellite-1 (ALOS), Sentinel-2A multispectral imagery and geographic information system (GIS) vector layers of Kuwait. The GCPs of the global navigation satellite system (GNSS) were recorded using a Catalyst Tremble unit. The GCPs had an average vertical accuracy of ±11 cm (median = 55 cm) and were even distributed over Kuwait's land surface. The ALOS synthetic aperture radar sensor records using the L-band (1.27 GHz) with various polarizations and spatial resolutions. The ALOS data is stored as GeoTIFF images, containing a digital elevation model (DEM) data with a spatial resolution of 10 m and vertical accuracy of ±15 m; the data have already been radiometrically and geometrically corrected. The ALOS data were downloaded from the Alaska Satellite Facility website (https://asf.alaska.edu).

The Sentinel-2A level-1C images were downloaded from the Copernicus website (https://scihub.copernicus.eu); the level-1C products are radiometric and geometrically corrected by the European Space Agency. Sentinel-2A images over Kuwait were obtained on 28th October 2018 and 27th November 2018, before and after a massive flash flood event. The images were used to classify land-cover features and determine flooded areas. Moreover, GIS vector layers containing national and districts borders were obtained from Kuwait Environmental Public Authority (https://epa.gov.kw).

A.1.2. DEM calibration

The DEM layer was used to derive terrain-based analysis layers, including slope, aspect and drainage network layers. Thus, the DEM accuracy significantly influences the flood risk map reliability. To improve the accuracy of the DEM layer used to map the flash flood risks, we modelled the relationship between 2991 GCPs and the ALOS DEM layer using regression analysis (figure 3(a)). The DEM model accuracy was assessed using a 5-fold cross-validation analysis (CVA). The model significantly estimated the elevation values ($r^2 = 0.985$, RMSE ± 3.6 m, and P-value $\ll$ 00.1) (figure 3(b)); the CVA result revealed that the model was very robust and consistent ($r^2 = 0.984$, RMSE ± 3.6 m). The statistical analysis was conducted using the R programming language.

A.1.3. Flash flood risk mapping

The flood risk mapping went through five main steps:

1. creating an accurate DEM layer,
2. modelling the stream network for Kuwait's land surface,
3. analysing 13 conditioning factors of flood risks to find the most significant ones,
4. building a spatial model using the most significant factors to map flood risks in Kuwait, and
5. assessing the spatial model accuracy.

The flood risk spatial model was built based on ten factors derived from surface analyses and remotely sensed data (figure 4). The model accuracy was evaluated using area under curve (AUC) method and the overall accuracy percentage; the AUC and the overall accuracy were 81% and 80%, respectively. The most significant factor was flood accumulation, whereas the slope was the least important factor (figure 5).

A.2. Exposure and vulnerability

In addition to secondary source data on the dynamics that drive disaster risk, we conducted our own

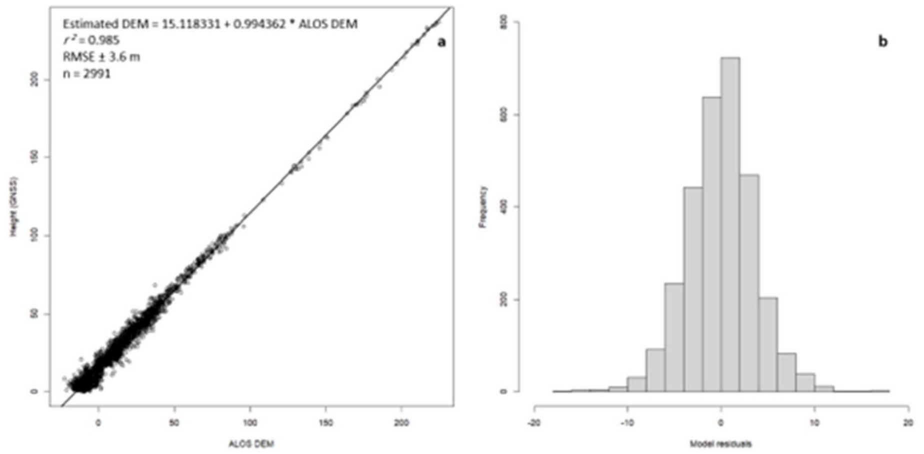

Figure 3. (a) The relationship between GCPs (height [GNSS]) and ALOS DEM was statistically significant. (b) The model residuals were normally distributed.

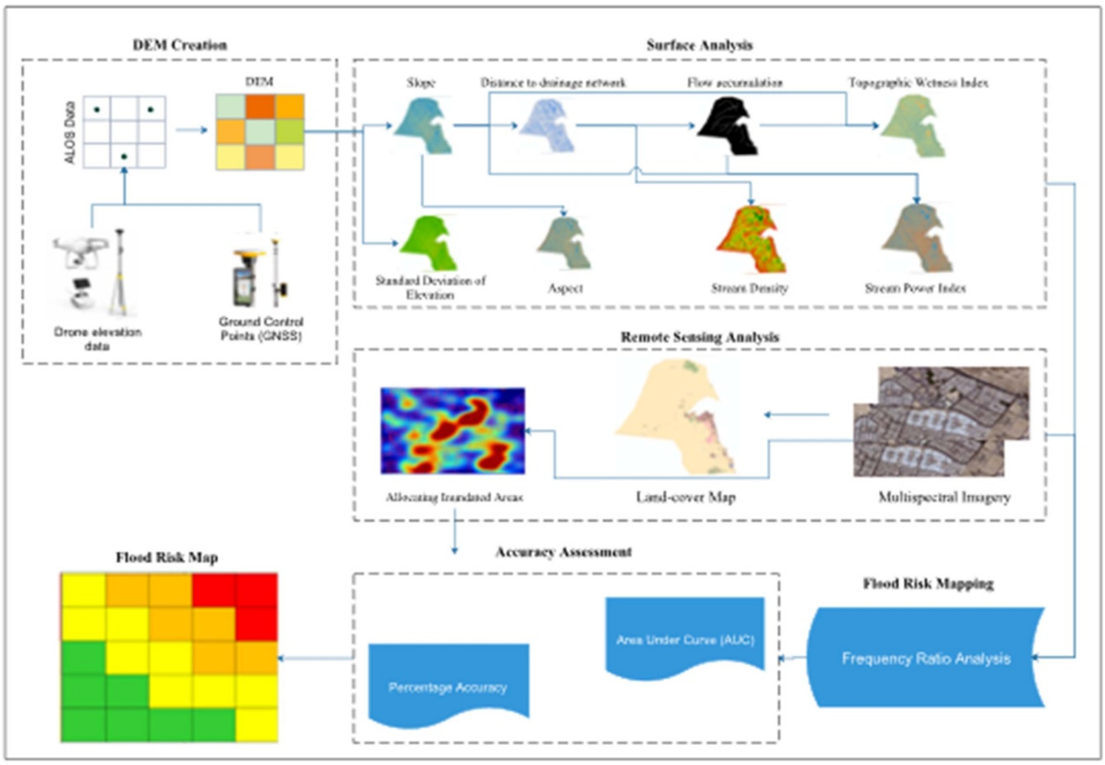

Figure 4. Illustration of the overall method.

analysis on flash flood risk in Kuwait. For the exposure to flash floods combine the flash flood hazard maps described in the previous section with all 165 000 building polygons of residential buildings in the Kuwait metro area from (Perkins and Will 2020). We classify the building polygons into eight urban expansion periods since the 1950s (1950–1967, 1967–1970, 1970–1977, 1977–1983, 1983–1995, 1995–2004, 2004–2010, 2010–2020) as identified by (Alkhuzamy Aziz and Alghais 2021) to reconstruct the temporal development of the exposure of residential buildings to flash flood hazards. Given that the spatial resolution of the flash flood hazard map is higher than the size of most building footprints we extract the minimum, maximum and mean values for flash flood susceptibility for each building polygon. We calculate the share of residential buildings with high exposure to flash floods for each of the eight urban expansion periods by dividing the total number of buildings built during each urban expansion period by the number of buildings that are in the 10th percentile of flash flood susceptibility (i.e. flash flood susceptibility index $\geqslant$90).

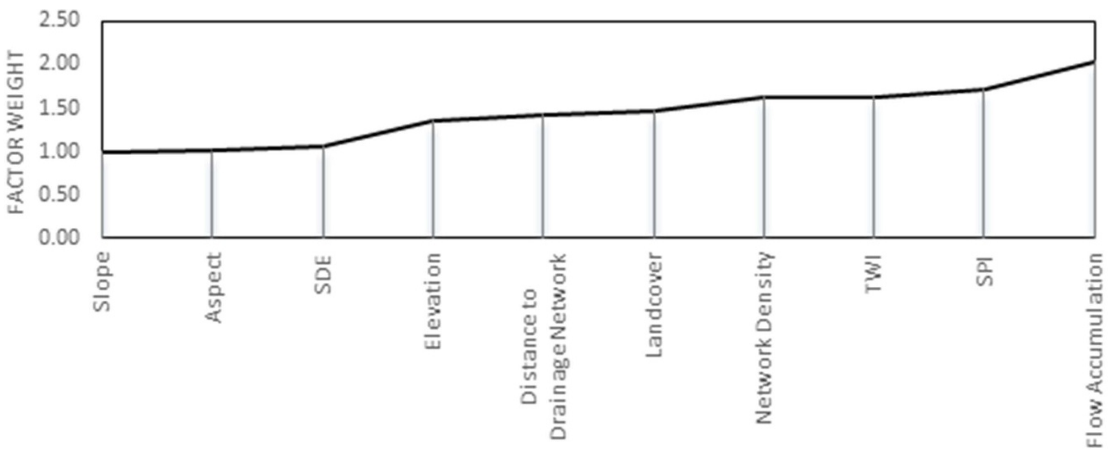

Figure 5. Weights of each factor used in the flood risk model.

For the vulnerability analysis, we construct a longitudinal micro data set of the population on the neighbourhood block level (median population per neighbourhood block 4267) in 5 year increments from 1975 to 2020 including projection data for 2040. For that we use dasymetric mapping to match the population data from the Global Human Settlement Layers from 1975 to 2020 with a 100 m spatial resolution to the neighbourhood block level (Schiavina *et al* 2022). The resulting population for each neighbourhood block is then proportionally adjusted to match the total population number of Kuwait based on census data for the respective year. Given the large and growing proportion of non-Kuwaiti citizens (or expats) and their higher social vulnerability to flooding as a result of their significantly worse economic and housing conditions, we focus our vulnerability analysis on the different flash flood susceptibilities between the Kuwaiti and non-Kuwaiti population. To downscale the national level numbers on the Kuwaiti and non-Kuwaiti population we use iterative proportional fitting, a spatial microsimulation method described in (Lovelace and Dumont 2017). Using the *mipfp* package in R (Barthélemy and Suesse 2018), we take the neighbourhood block level information on the Kuwaiti and non-Kuwaiti population from the 2011 official Kuwait census as the target marginal distribution to determine the Kuwaiti and non-Kuwaiti population for each year of analysis (1975–2020). The resulting dataset containing the number of Kuwaitis and non-Kuwaitis living in each neighbourhood block for the 5 year increments from 1975 and 2020 is then combined with the flash flood susceptibility map. The population in each neighbourhood block is randomly distributed and point values of the flash flood susceptibility are extracted. The process is repeated in an ensemble of 1000 runs to quantify the uncertainty of the flash flood susceptibility. For the vulnerability analysis, we count the number of Kuwaitis and non-Kuwaitis in each neighbourhood block for each analysis year from 1975 to 2020 which are in the 10th percentile of flash flood susceptibility (i.e. flash flood susceptibility index $\geqslant$90). We use the same procedure for the population projections for the Kuwaiti and non-Kuwaiti population by 2040, which is provided on the neighbourhood block level as part of the 4th Kuwait master plan (Perkins and Will 2020).

ORCID iD

Viktor Rözer https://orcid.org/0000-0002-2883-5347

References

Al-Abdullah Y M, Al-Ragom F, Al-Sayegh O, Sreekanth K, Malyshev T, Heaps C, Ocal U and Nassar M 2019 Kuwait energy outlook—sustaining prosperity through strategic energy management *Technical Report* (Kuwait Institute for Scientific Research) (available at: www.kisr.edu.kw/media/filer_public/a7/d7/a7d7ecfa-242e-4c5f-a9bc-f971295b0a41/keo_report_english.pdf) (Accessed 27 June 2024)

Al-Damkhi A M, Khuraibet A M, Al-Attar F A-H and Abdul-Wahab S A 2008 Integrating environmental impact assessment within Kuwait master plans as a tool for human and ecological risk control *Hum. Ecol. Risk Assess.* **14** 1070–85

Al-Hemoud A, Gasana J, Al-Dabbous A, Alajeel A, Al-Shatti A, Behbehani W and Malak M 2019 Exposure levels of air pollution (PM2.5) and associated health risk in Kuwait *Environ. Res.* **179** 108730

Al-Nakib F 2013 Kuwait's modern spectacle: oil wealth and the making of a new capital city, 1950–90 *Comp. Stud. South Asia Afr. Middle East* **33** 7–25

Al-Nakib F 2016 *Kuwait Transformed: A History of oil and Urban Life* (Stanford University Press)

Al-Qallaf H, Aliewi A and Abdulhadi A 2020 Assessment of the effect of extreme rainfall events on temporal rainfall variability in Kuwait *Arab. J. Geosci.* **13** 1–11

Alahmad B, Vicedo-Cabrera A M, Chen K, Garshick E, Bernstein A S, Schwartz J and Koutrakis P 2022 Climate change and health in Kuwait: temperature and mortality projections under different climatic scenarios *Environ. Res. Lett.* **17** 074001

Alkhuzamy Aziz M and Alghais N 2021 Cartographic analysis of urban expansion in Kuwait *Cartographica: Int. J. Geogr. Inf. Geovisualization* **56** 183–207
Alsahli M M and Al-Harbi M 2022 Environmental justice in Kuwait metropolitan area: a spatial analysis of land-use impact on environmental quality variability *Local Environ.* **28** 80–98
Alsahli M M and AlHasem A M 2016 Vulnerability of Kuwait coast to sea level rise *Dan. J. Geogr.* **116** 56–70
Alsayegh O, Saker N and Alqattan A 2018 Integrating sustainable energy strategy with the second development plan of Kuwait *Renew. Sustain. Energy Rev.* **82** 3430–40
Alshalfan S 2013 The right to housing in Kuwait: an urban injustice in a socially just system (Kuwait Programme on Development, Governance and Globalisation in the Gulf States) (available at: http://eprints.lse.ac.uk/55012/1/__Libfile_repository_Content_Kuwait%20Programme_Alshalfan_2013.pdf) (Accessed 27 June 2024)
Alshalfan S, Alrasheed D S and Albabtain B 2022 Housing Kuwaitis *Technical Report* (Kuwait Foundation for the Advancement of Sciences) (available at: www.kfas.org/Publications/Housing-Kuwaitis) (Accessed 27 June 2024)
Ansari D and Holz F 2020 Between stranded assets and green transformation: fossil-fuel-producing developing countries towards 2055 *World Dev.* **130** 104947
Arman H, Iammarino S, Ibarra-Olivo J E and Lee N 2022 Systems of innovation, diversification and the R&D trap: a case study of Kuwait *Sci. Public Policy* **49** 179–90
Balasbaneh A T, Marsono A K B and Gohari A 2019 Sustainable materials selection based on flood damage assessment for a building using LCA and LCC *J. Clean. Prod.* **222** 844–55
Bang G and Lahn B 2020 From oil as welfare to oil as risk? Norwegian petroleum resource governance and climate policy *Clim. Policy* **20** 997–1009
Baran J, Szpor A and Witajewski-Baltvilks J 2020 Low-carbon transition in a coal-producing country: a labour market perspective *Energy Policy* **147** 111878
Barthélemy J and Suesse T 2018 mipfp: an R package for multidimensional array fitting and simulating multivariate Bernoulli distributions *J. Stat. Softw.* **86** 1–20
Bates P D, Savage J, Wing O, Quinn N, Sampson C, Neal J and Smith A 2023 A climate-conditioned catastrophe risk model for uk flooding *Nat. Hazards Earth Syst. Sci.* **23** 891–908
Batten S 2018 Climate change and the macro-economy: a critical review *Bank of England Working paper* 706 (available at: www.bankofengland.co.uk/-/media/boe/files/working-paper/2018/climate-change-and-the-macro-economy-a-critical-review.pdf) (Accessed 27 June 2024)
Batten S, Sowerbutts R and Tanaka M 2016 Let's talk about the weather: the impact of climate change on central banks *Bank of England Working paper* 603 (available at: www.bankofengland.co.uk/-/media/boe/files/working-paper/2016/lets-talk-about-the-weather-the-impact-of-climate-change-on-central-banks.pdf) (Accessed 27 June 2024)
Bos K and Gupta J 2019 Stranded assets and stranded resources: implications for climate change mitigation and global sustainable development *Energy Res. Soc. Sci.* **56** 101215
Bridge G, Bouzarovski S, Bradshaw M and Eyre N 2013 Geographies of energy transition: space, place and the low-carbon economy *Energy Policy* **53** 331–40
Callen M T, Cherif R, Hasanov F, Hegazy M A and Khandelwal P 2014 Economic diversification in the GCC: past, present, and future *Staff Discussion Notes* 2014/012 (available at: www.imf.org/en/Publications/Staff-Discussion-Notes/Issues/2016/12/31/Economic-Diversification-in-the-GCC-Past-Present-and-Future-42531) (Accessed 27 June 2024)
Calverley D and Anderson K 2022 *Phaseout Pathways for Fossil Fuel Production Within Paris-compliant Carbon Budgets* (Tyndall Centre, University of Manchester) (available at: https://pure.manchester.ac.uk/ws/portalfiles/portal/213256008/Tyndall_Production_Phaseout_Report_final_text_3_.pdf) (Accessed 27 June 2024)
Carattini S, Heutel G and Melkadze G 2023 Climate policy, financial frictions and transition risk *Rev. Econ. Dyn.* **51** 778–94
CIA 2024 World factbook—Kuwait (available at: www.cia.gov/the-world-factbook/countries/kuwait/) (Accessed 27 June 2024)
ClimateWatch 2023 Historical GHG emissions—Kuwait (available at: www.climatewatchdata.org/embed/countries/KWT/ghg-emissions?end_year=2019&start_year=1990#ghg-emissions) (Accessed 27 June 2024)
Dietz S, Bowen A, Dixon C and Gradwell P 2016 Climate value at risk of global financial assets *Nat. Clim. Change* **6** 676–9
Doblas-Reyes F J *et al* 2021 Linking global to regional climate change *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (Cambridge University Press) pp 1363–512
Dow K, Berkhout F, Preston B L, Klein R J, Midgley G and Shaw M R 2013 Limits to adaptation *Nat. Clim. Change* **3** 305–7
Enerdata 2023 Kuwait energy information (available at: www.enerdata.net/estore/energy-market/kuwait/) (Accessed 27 June 2024)
Fankhauser S 2010 The costs of adaptation *Wiley Interdiscip. Rev.-Clim. Change* **1** 23–30
Field C B, Barros V, Stocker T F and Dahe Q 2012 *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press)
Fisch-Romito V and Guivarch C 2019 Transportation infrastructures in a low carbon world: an evaluation of investment needs and their determinants *Transp. Res.* D **72** 203–19
Foxon T J 2011 A coevolutionary framework for analysing a transition to a sustainable low carbon economy *Ecol. Econ.* **70** 2258–67
Friedlingstein P *et al* 2022 Global carbon budget 2022 *Earth Syst. Sci. Data* **14** 4811–900
García-García P, Carpintero O and Buendía L 2020 Just energy transitions to low carbon economies: a review of the concept and its effects on labour and income *Energy Res. Soc. Sci.* **70** 101664
Garvey A, Norman J B, Büchs M and Barrett J 2022 A "spatially just" transition? A critical review of regional equity in decarbonisation pathways *Energy Res. Soc. Sci.* **88** 102630
Gelan A, Hewings G J and Alawadhi A 2021 Diversifying a resource-dependent economy: private–public relationships in the Kuwaiti economy *J. Econ. Struct.* **10** 1–22
Griggs G and Reguero B G 2021 Coastal adaptation to climate change and sea-level rise *Water* **13** 2151
Hanson S E and Nicholls R J 2020 Demand for ports to 2050: climate policy, growing trade and the impacts of sea-level rise *Earth's Future* **8** e2020EF001543
Hassan A, Albanai J A and Goudie A 2024 Modeling and managing flash flood hazards in the state of Kuwait: a hydrogeomorphological study *Hydroclimatic Extremes in the Middle East and North Africa* (Elsevier) pp 129–47
Hassan A and Hassaan M A 2020 Potential impact of sea level rise on the geomorphology of Kuwait state coastline *Arab. J. Geosci.* **13** 1–16
Heede R 2014 Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010 *Clim. Change* **122** 229–41
Hertog S 2020 Reforming wealth distribution in Kuwait: estimating costs and impacts *Kuwait Programme, LSE Middle East Centre* (available at: https://eprints.lse.ac.uk/105564/2/Reforming_Wealth_Distribution_in_Kuwait_New.pdf) (Accessed 27 June 2024)
Hewins R 1963 *A Golden Dream: The Miracle of Kuwait* (WH Allen)
Hitz S and Smith J 2004 Estimating global impacts from climate change *Glob. Environ. Change* **14** 201–18

Howarth C and Robinson E J 2024 Effective climate action must integrate climate adaptation and mitigation *Nat. Clim. Change* **14** 300–1
Hurlimann A, Moosavi S and Browne G R 2021 Urban planning policy must do more to integrate climate change adaptation and mitigation actions *Land Use Policy* **101** 105188
Ioannidou D, Sonnemann G and Suh S 2020 Do we have enough natural sand for low-carbon infrastructure? *J. Ind. Ecol.* **24** 1004–15
Kennedy C and Corfee-Morlot J 2013 Past performance and future needs for low carbon climate resilient infrastructure–an investment perspective *Energy Policy* **59** 773–83
Klein R, Huq S, Denton F, Downing T, Richels R, Robinson J and Toth F 2007 Inter-relationships between adaptation and mitigation *Climate Change 2007-Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC* vol 4 (Cambridge University Press) ch 18
Lazarus E D 2022 The disaster trap: cyclones, tourism, colonial legacies and the systemic feedbacks exacerbating disaster risk *Trans. Inst. Br. Geogr.* **47** 577–88
Lenton T M and Ciscar J-C 2013 Integrating tipping points into climate impact assessments *Clim. Change* **117** 585–97
Lesnikowski A, Ford J, Biesbroek R, Berrang-Ford L, Maillet M, Araos M and Austin S E 2017 What does the Paris Agreement mean for adaptation? *Climate Policy* **17** 825–31
Lovelace R and Dumont M 2017 *Spatial Microsimulation with R* (Chapman and Hall/CRC)
Marin G and Modica M 2017 Socio-economic exposure to natural disasters *Environ. Impact Assess. Rev.* **64** 57–66
McGlade C and Ekins P 2015 The geographical distribution of fossil fuels unused when limiting global warming to 2C *Nature* **517** 187–90
Mishrif A 2018 Challenges of economic diversification in the GCC countries *Economic Diversification in the Gulf Region, Volume II: Comparing Global Challenges* (Springer) pp 1–19
Mohammed S, Desha C and Goonetilleke A 2022 Investigating low-carbon pathways for hydrocarbon-dependent rentier states: economic transition in Qatar *Technol. Forecast. Soc. Change* **185** 122084
Müller D B, Liu G, Løvik A N, Modaresi R, Pauliuk S, Steinhoff F S and Brattebø H 2013 Carbon emissions of infrastructure development *Environ. Sci. Technol.* **47** 11739–46
Neelamani S, Al-Houti D, Al-Ragum A, Al-Salem K and Al-Saleh A H 2022 Assessment of coastal inundation cost due to future sea level rise: a case study for Kuwait *Mar. Georesour. Geotechnol.* **40** 523–37
Niamir L, Filatova T, Voinov A and Bressers H 2018 Transition to low-carbon economy: assessing cumulative impacts of individual behavioral changes *Energy Policy* **118** 325–45
Nilsson E 2017 Urban memory and preservation in Kuwait: a case study of Souk Al Wataniya *The Politics of Memory, Territory, and Heritage in Iraq and Syria* (Society of Architectural Historians) (available at: https://sah.hcommons.org/deposits/objects/hc:30182/datastreams/CONTENT/content) (Accessed 27 June 2024)
Olver-Ellis S 2020 Building the new Kuwait: vision 2035 and the challenge of diversification *Kuwait Programme, LSE Middle East Centre* (available at: https://eprints.lse.ac.uk/103198/1/Olver_Ellis_building_the_new_Kuwait_published.pdf) (Accessed 27 June 2024)
Otto I M, Reckien D, Reyer C P, Marcus R, Le Masson V, Jones L, Norton A and Serdeczny O 2017 Social vulnerability to climate change: a review of concepts and evidence *Reg. Environ. Change* **17** 1651–62
Pal J S and Eltahir E A 2016 Future temperature in southwest Asia projected to exceed a threshold for human adaptability *Nat. Clim. Change* **6** 197–200
Pan W 2014 Briefing: delivering buildings and infrastructure towards zero carbon *Infrastruct. Asset Manage.* **1** 60–65
Perkins and Will 2020 4th Kuwait Masterplan 2040—towards a smart state *Technical Report* (Council of Ministers)
Rockström J *et al* 2009 Planetary boundaries: exploring the safe operating space for humanity *Ecol. Soc.* **14** 32 (available at: http://www. ecologyandsociety.org/vol14/iss2/art32/)
Schiavina M *et al* 2022 GHSL data package 2022 *Technical Report JRC* 129516 (Publications Office of the European Union) (https://doi.org/10.2760/526478)
Semieniuk G, Campiglio E, Mercure J-F, Volz U and Edwards N R 2021 Low-carbon transition risks for finance *Wiley Interdiscip. Rev.-Clim. Change* **12** e678
Semieniuk G, Holden P B, Mercure J-F, Salas P, Pollitt H, Jobson K, Vercoulen P, Chewpreecha U, Edwards N R and Viñuales J E 2022 Stranded fossil-fuel assets translate to major losses for investors in advanced economies *Nat. Clim. Change* **12** 532–8
Seneviratne S I *et al* 2021 Weather and climate extreme events in a changing climate *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed P Z Masson-Delmotte *et al* (Cambridge University Press) pp 1513–766
Sharifi A 2020 Trade-offs and conflicts between urban climate change mitigation and adaptation measures: a literature review *J. Clean. Prod.* **276** 122813
Shiber S G 1964 *Kuwait Urbanization: Documentation, Analysis, Critique* (Kuwait Government Printing Press)
Siderius C, Conway D, Yassine M, Murken L, Lostis P-L and Dalin C 2020 Multi-scale analysis of the water-energy-food nexus in the Gulf region *Environ. Res. Lett.* **15** 094024
Sim L-C 2020 Low-carbon energy in the Gulf: upending the rentier state? *Energy Res. Soc. Sci.* **70** 101752
Simpson N P *et al* 2021 A framework for complex climate change risk assessment *One Earth* **4** 489–501
Stott P 2016 How climate change affects extreme weather events *Science* **352** 1517–8
Tariq H, Pathirage C and Fernando T 2021 Measuring community disaster resilience at local levels: an adaptable resilience framework *Int. J. Disaster Risk Reduct.* **62** 102358
TCFD 2017 The use of scenario analysis in disclosure of climate-related risks and opportunities—technical supplement *Technical Report* (Task Force on Climate-Related Financial Disclosures) (available at: https://assets.bbhub.io/company/sites/60/2020/10/FINAL-2017-TCFD-Report-11052018.pdf) (Accessed 27 June 2024)
Thiollet H 2016 Managing migrant labour in the Gulf: transnational dynamics of migration politics since the 1930s *International Migration Institute—Working Papers* 131 (available at: https://hal.science/hal-01346366) (Accessed 27 June 2024)
Tol R S, Downing T E, Kuik O J and Smith J B 2004 Distributional aspects of climate change impacts *Glob. Environ. Change* **14** 259–72
Tran T H and Egermann M 2022 Land-use implications of energy transition pathways towards decarbonisation–comparing the footprints of Vietnam, New Zealand and Finland *Energy Policy* **166** 112951
Van de Graaf T and Verbruggen A 2015 The oil endgame: strategies of oil exporters in a carbon-constrained world *Environ. Sci. Policy* **54** 456–62
Van der Ploeg F and Rezai A 2020 Stranded assets in the transition to a carbon-free economy *Annu. Rev. Resour. Econ.* **12** 281–98
While A and Eadson W 2022 Zero carbon as economic restructuring: a spatial divisions of labour and just transition *New Polit. Econ.* **27** 385–402

While A, Jonas A E and Gibbs D 2010 From sustainable development to carbon control: eco-state restructuring and the politics of urban and regional development *Trans. Inst. Br. Geogr.* **35** 76–93

Winsemius H C *et al* 2016 Global drivers of future river flood risk *Nat. Clim. Change* **6** 381–5

Zachmann G 2022 The role of competition in the transition to climate neutrality *Technical Report* (Bruegel Working paper) (available at: https://www.bruegel.org/working-paper/role-competition-transition-climate-neutrality)

Zhang D, Xu Z, Li C, Yang R, Shahidehpour M, Wu Q and Yan M 2019 Economic and sustainability promises of wind energy considering the impacts of climate change and vulnerabilities to extreme conditions *Electr. J.* **32** 7–12

Zittis G *et al* 2022 Climate change and weather extremes in the Eastern Mediterranean and Middle East *Rev. Geophys.* **60** e2021RG000762