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Adaptation of interconnected infrastructures to climate change: A socio-technical systems perspective

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ABSTRACT

Climate change is likely to affect how society will function in this century. Because climate change effects may be severe, a next step is to study not only the effects on natural systems, but also the effects on built infrastructure systems and, in response to anticipated effects, the adaptation of those systems. Studies that discuss interconnected infrastructures, society's backbones, in light of climate change are emerging. We apply a socio-technical systems perspective in order to gain insight into the effects of climate change on our infrastructure systems and possible adaption strategies for the coming decades. We use this perspective to collect and describe the literature on adaptation of infrastructures to climate change. We find that the analysed papers predominantly focus on specific geographic areas and that various types of impacts on and interdependencies of built socio-technical systems are recognized, not only for energy and transport, but also for water infrastructures. A missing step is the modelling of adaptation measures. Recent literature enables an exploration of strategies for adaptation, which should be expected in the coming years.

1. Introduction

Climate change is likely to affect the way in which society will function in this century (IPCC, 2007). Scientific consensus is in favour of accepting climate change and the seriousness of its potential impacts (Doran and Kendall, 2009; IPCC, 2007). There is a vast body of literature on climate change itself and the effects on our natural environment. Recent literature shows that serious impacts may be expected on our infrastructures as well (e.g. Decicco and Mark, 1998; Hor et al., 2005; Van Vliet et al., 2012), systems that form the backbones of society and are fundamental for many of our daily activities (Chappin, 2011). There is an increasing awareness of the interdependencies of infrastructures (e.g. Wilbanks and Fernandez, 2003), such as the effects of the water infrastructure on health (e.g. Costello et al., 2009). Nevertheless, climate change effects on interconnected energy, transport, and built infrastructures remain less studied in the scientific literature (Hunt and Watkiss, 2011; Bollinger et al., 2013).[1] Throughout the current literature, the nature of the expected consequences stresses the need for adaptation. Consequently, mitigation (reducing our impact on the climate) may prove insufficient to safeguard the proper functioning our infrastructures in the coming decades. When severe consequences of climate change occur, adaptation (anticipating and responding to the impacts of climate change) may be crucial. Awareness of how to adapt infrastructures against the consequences of climate change is essential for considering what to do now in order to assure provision for energy and transport services in the decades to come. This paper's objective is to analyse and provide an overview of scientific studies of interconnected (energy and transport) infrastructures in this area.

We frame infrastructures as complex socio-technical systems (de Bruijn and Herder, 2009; Van der Lei et al., 2010; Chappin, 2011), which are large-scale systems with a huge number of elements and their connections. As illustrated in Fig. 1, this includes the technical infrastructure systems and networks such as roadways and electricity grids. Goods or services flow through these systems and networks and thus, the technical infrastructure provides the basis for many daily activities. Socio-technical systems thinking suggests that in order to shape this infrastructure, the “social elements and the corresponding relations must also be considered as belonging to the system” (Ottens et al., 2006, pp. 133). The social infrastructure includes the humans, organizations and governments that make decisions and form our economy as well as our institutions and policies. Purposive actors in the system

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[1] Interdependencies suggest the influence that infrastructures have on each other, i.e. the effects across infrastructures and the dependencies that follow. Various interdependencies are often acknowledged and described. In this paper we focus on the underlying but less studied connections between the infrastructures, which we label as interconnectedness.

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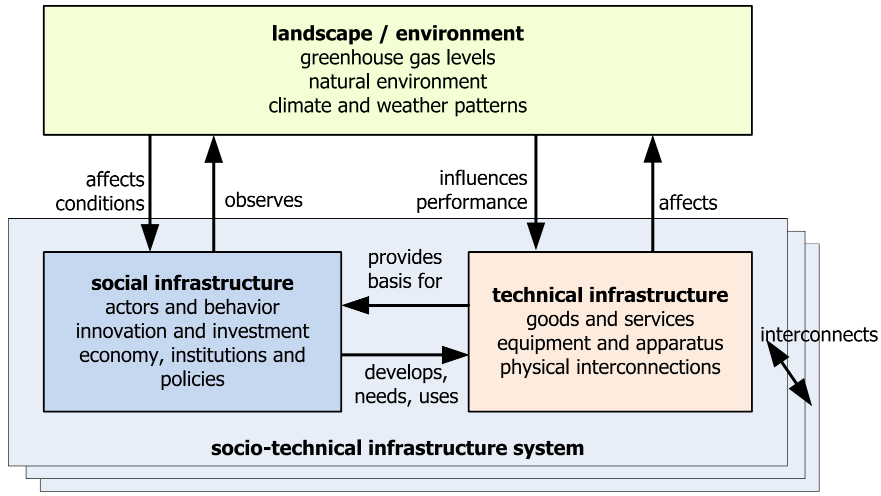

Fig. 1. Socio-technical system's perspective on climate-affected infrastructures. Adaptation implies changing (elements of) the socio-technical infrastructure system.

develop, need and use the technical artefacts, in order to function. The effort to adapt follows the observation of (expected) patterns in the so-called 'landscape' or environment, which includes the natural environment. This environment, including evolving greenhouse gas levels, climate and weather patterns, affects and is affected by the performance of the socio-technical infrastructure system.

In order to understand better how to govern our infrastructures, we have to accept that "change in social elements and technological elements cannot be fully separated" (Chappin, 2011: p. 3). Applying this perspective to the interdependencies of infrastructures implies study of the myriad of interconnections: i.e. 1) those between technical elements, 2) those between the social elements and 3) those between the social and technical elements, all within and across infrastructures. This is also needed in order to study *adaptation* of these systems, which suggests making purposeful changes to one or more of the various elements of the interconnected socio-technical infrastructure systems currently in place. In this paper, we use the socio-technical systems perspective as a basis for a literature review on climate change adaptation, focussing on energy and transport infrastructures.

In Section 2 we describe the review approach. The results of the literature review are presented in Section 3. In Section 4, we discuss the findings and draw conclusions.

2. Approach

We conducted a literature search in the scientific database Scopus[2]. We limited the scope of our search to articles pertaining to climate change or global warming. Furthermore, because we are mainly interested in interconnected infrastructures we searched for a single combination of two specific infrastructures, i.e. energy and transport infrastructures. The results, however, include findings across various infrastructures.

We expected to find a reasonable number of papers when we added *adaptation* as a required search term, but that search lead remarkably to only 4 results (i.e. Jollands et al., 2007; Younger et al., 2008; Prowse et al., 2009; Hunt et al., 2011). This does not necessarily imply, and our results confirm, that this is all the literature on adaptation of energy and transport infrastructures. In order to do a meaningful analysis, we broadened the analysis to the 258 papers that were obtained by also allowing for the term *impact*.

In order to focus our results, we narrowed the selection down by an analysis of the relevance of the papers on the basis of their title. Papers are excluded if the title (or the abstract) strongly indicates a focus on individual technical elements. We ended up with 54 papers for which the full text of 48 papers could be retrieved.[3]

We analysed the sample of papers from a socio-technical systems perspective on infrastructures (see Fig. 1). We assessed which papers include an analysis of interconnected infrastructures and report on which *systems* are covered and whether the research focus is on the technical, the social and/or the landscape aspect of the systems perspective.

In order to make our analysis more thorough, we characterize the various studies in terms of time frame (long term, >10 years, medium term 1–10 years and short-term <1 year); the core methodology (quantitative or qualitative); whether the analysis is about adaptation (or about mitigation instead); and which climate change aspects are covered.

3. Results

In this section we describe the results with respect to mitigation and adaptation and interconnected infrastructure systems. The complete list of results can be found in Table 5 (see Appendix).

3.1. Mitigation and adaptation

The papers can be categorized into five groups: climate change impact, mitigation measures, conceptualizing adaptation, enabling adaptation, and design or selection of adaptation strategies (See Table 1).

3.1.1. Climate change impact

The largest group of the retrieved papers do not discuss adaptation, but focus instead on the impacts of climate change or extreme weather patterns, a consequence of including *impact* as search term. A considerable part of this literature focuses on

[2] Scopus (www.scopus.com) is an important database of scientific literature covering a wide range of journals. See Falagas et al. (2008) for a comparison to other popular databases.

[3] The final search query in Scopus was ("climate change" OR "global warming") AND infrastructure AND energy AND transport AND (impact OR adaptation). The search was limited to title, keywords and abstract.

Table 1
Papers clustered on climate change impact, mitigation measures and adaptation (conceptualizing, enabling and strategies).

Climate change impact (16)	Mitigation measures (8)	Conceptualizing adaptation (2)	Enable adaptation (11)	Adaptation strategies (12)
Becker (2011)	Decicco and Mark (1998)	Fankhauser et al. (1999)	Brown and Lall (2006)	Arndt et al. (2011)
Belzer et al. (1996)	García-Montero et al. (2010)	Smith (1997)	Jollands et al. (2007)	Evans (2011)
Costello et al. (2009)	Keith et al. (2006)		Mackay and Last (2010)	Frederick (1997)
Davis et al. (2010)	Liu et al. (2007)		Pearce et al. (2011)	Hunt and Watkiss (2011)
Easterling et al. (2000)	Powlson et al. (2005)		Schandl and Turner (2009)	Kirshen and Ruth (2004)
Eum and Simonovic (2012)	Sanden and Azar (2005)		Stakhiv (2010)	Kirshen et al. (2008)
Fuglestvedt et al. (2010)	Scheer (2011)		Suarez et al. (2005)	Mcmichael and Sari Kovats (2000)
Gasper et al. (2011)	Schwoon (2008)		Tol et al. (2003)	Miles et al. (2010)
Greenough et al. (2001)			Vellinga and Klein (1993)	Rosenzweig et al. (2011)
Hoffert (2010)			Shen et al. (2011)	Ruth et al. (2007)
Koetse and Rietveld (2009)				
Krol et al. (2006)				
Lynch et al. (2004)				
Wilby (2007)				
Woodcock et al. (2007)				
Wuebbles et al. (2010)				

impacts in a particular region, such as the Upper Thames River basin (Eum and Simonovic, 2012), a region in Brazil (Krol et al., 2006), Alaska (Lynch et al., 2004), Chicago (Wuebbles et al., 2010), and the built environment of London (Wilby, 2007).

The second subgroup is broad and addresses societies. Prime examples are impacts on the broader societal infrastructure (Easterling et al., 2000), social and economic impacts on the urban environment (Gasper et al., 2011), and impacts on the social system (Becker, 2011; Belzer et al., 1996; Costello et al., 2009) and on health (Greenough et al., 2001; Woodcock et al., 2007).

In the third subgroup, infrastructures play a central role. Applied to *transport*, Hoffert (2010) discusses the role of fossil fuels and future emissions, Koetse and Rietveld (2009) review various impacts, and Fuglestvedt et al. (2010) develop suitable metrics for transport impacts. Focussing on *energy*, Davis et al. (2010) focus on CO_2 emissions of the existing power infrastructure and effects on global warming.

3.1.2. Mitigation policies/measures

The second group focuses on developing measures that deal with climate change impacts. A first subgroup predominantly focuses on possibilities for CO_2 reduction for 1) the transport domain in terms of reduction of greenhouse gas emissions from transport (Decicco and Mark, 1998), fuel cell vehicles (Schwoon, 2008) and 2) the energy domain in terms of CO_2 capture and storage (Scheer, 2011; García-Montero, 2010; Keith et al., 2006), selecting technologies (Liu et al., 2007).

A second subgroup focuses on methodological developments for policies and or measures, i.e. a modelling approach that allows development of policies (Warren et al., 2008) and a discussion of the pros and cons of economy-wide and technology-specific approaches for carbon-reduction targets (Sanden and Azar, 2005).

3.1.3. Conceptualizing adaptation

A number of papers deal explicitly with conceptualizing adaptation, and provide suggestions for developing adaptation strategies. Fankhauser et al. (1999) consider three dimensions of strategic adaptation:

- Reactive adaptation is in face of actual impacts, whereas anticipatory adaptation is applied before these impacts occur.
- Planned adaptations are specific and well-thought adaptation options, whereas autonomous options are made without overall planning.
- Substitutes are sets of adaptation strategies that are exchangeable, whereas compliments are sets of adaptation strategies that work together.

Smith (1997) goes one step further to develop criteria that can be used to assess whether adaptation policy is needed. He stresses the fact the policies made to adapt to climate change should in the first place be flexible and have benefits that outweigh costs.

3.1.4. Enabling adaptation

Part of the literature does not focus on the selection of a strategy but provides insights that can inform choices among strategies.

A first subgroup develops indicators and models for measurements. Prime examples are Brown and Lall (2006), who develop an index for rainfall in order to be able to assess infrastructure needs and Schandl and Turner (2009), who develop a dematerialization model and test different policies for Australia that addresses materials, energy, water use and resulting CO_2 emissions. Shen et al. (2011) develop a life-cycle assessment model to study optimal policy for PET bottle recycling.

The second subgroup uses case studies to identify new areas for which adaptation approaches should be developed. Examples are an inventory of the vulnerabilities of Hamilton, New Zealand, for which policies are needed (Jollands et al., 2007), the need for policies that improve collaboration in the Canadian mining sector (Pearce et al., 2011), and for policies that address expected sea levels (Vellinga and Klein, 1993).

Some of those case studies are infrastructure-specific. With respect to *transport* networks, one study focuses on the need for more cost-effective policies than currently existing for the Boston area (Suarez et al., 2005). With respect to *water*, Tol et al. (2003) emphasize the need for lasting institutional reform to new infrastructure to mitigate flood risk in the Netherlands, and Mackay and Last (2010) and Stakhiv (2010) present models and approaches that enable the exploration of different water management strategies for a city.

3.1.5. Adaptation strategies (or options)

Various articles develop and discuss adaptation strategies. Focussing on *technical* systems, Miles et al. (2010) find that agriculture, energy, salmon, urban storm water infrastructure, forests, human health, coasts, and water resources of a US state are all sensitive to climate change and suggest adaptation strategies for these sectors.

Focussing on the *social* system, Evans (2011) argues for urban experiments from a resilience ecology perspective and argues that the actors are all part of the (socio-ecological) system. Frederick (1997) addresses the need for new institutions that are able to facilitate adaptation for the water system.

A number of papers focus on adaptation *costs*. Hunt and Watkiss (2011) review climate change effects of major cities in the world and assess the adaptation options that have been formulated with a

Table 2
The distribution of papers based on infrastructure focus and core methodology.

Infrastructures (24)				Not infrastructure (24)	
Interconnected (8)		Not interconnected (16)		Not interconnected (24)	
Quantitative (5)	Qualitative (3)	Quantitative (9)	Qualitative (7)	Quantitative (9)	Qualitative (15)

focus on cost and risk. In line with Smith (1997), Arndt et al. (2011) find that investments protecting coastal regions for Mozambique may not be worthwhile. They suggest that softer adaptation policies like rezoning of high-risk areas may be more cost effective in the long run.

Kirshen et al. (2008) are unique in that they explicitly study *interdependencies* of climate change effects and adaptation options: they argue that interrelations among infrastructure systems make it critical to develop an understanding of the impacts that adaptation options have on each other.

3.2. Interconnected infrastructure systems

Table 2 provides an overview of the distribution of the papers with respect to their infrastructure focus and core methodology (quantitative v. qualitative). Before we turn our focus to the 8 papers on interconnected infrastructures, we provide an overview of the types of systems (see Table 3) and methodologies (see Table 4).

3.2.1. Types of systems

The largest group of papers consider systems characterized by a specific **geographic scope**, such as countries/societies (Costello et al., 2009; Greenough et al., 2001; García-Montero et al., 2010), particular urban areas (Boston Metropolitan area, Suarez et al., 2005) or cities (Hunt and Watkiss, 2011). These papers describe one or a few infrastructures. A prominent example is the drinking water infrastructure in Hamilton, New Zealand (Ruth et al., 2007). An exception is García-Montero et al. (2010), who explicitly model the transport infrastructure of Spain and its impact *on* the climate.

The second group studied **infrastructure** systems. *Water* systems are popular, with a focus on water management (Frederick, 1997; Krol et al., 2006), but they typically include the natural systems surrounding the built infrastructure (e.g. by including coastal zones and river basins). An example is a study of the increased risk of river floods in the Netherlands, where floods systems as well as the institutional response against flooding are treated (Tol et al., 2003). The papers on *energy* and *transport* systems are more specific, such as options for energy technology (e.g. Scheer, 2011) and energy saving (e.g. Liu et al., 2007) or diffusion of fuel cell vehicles (Schwoon, 2008). Furthermore, the transport papers have a strong focus on CO_2 reduction policies (e.g. Deccicio and Mark, 1997).

The third group focuses on other systems, most prominently the **environment** (natural systems such as the atmosphere) and **buildings** (the built environment or their technical elements). They do not study infrastructures.

3.2.2. Methodologies

Overall, the papers are evenly divided in applying qualitative and quantitative methods (see Table 4). Popular *qualitative* methods include various qualitative analyses, reviews of existing literature, and summaries of policy documents. The latter are particularly interesting for the breadth of experiential insight they make available to the scientific community. The *quantitative* methods include various types of modelling and simulation.

Only 24 papers employ an explicit socio-technical systems perspective; these are more often than not focused on quantitative methods (see Table 2). The quantitative papers focus mainly on *energy* (5 out of 6) and *transport* (3 out of 4). *Water* infrastructures are mostly discussed qualitatively. Another surprise is a frequent focus on *landscape* aspects over technical or social aspects. Only a few papers demonstrate a complete socio-technical systems perspective, where both the technical and the social are represented.

A focus on long-term effects, for instance, predicts greenhouse gas emissions. However short-term effects, such as changed weather patterns, also are included. Papers combining the short-term *and* long-term effects of climate change are rather scarce (Hunt and Watkiss, 2011; Wuebbles et al., 2010).

3.2.3. Interconnections

Only 8 out of these 24 papers address interconnections between infrastructures; all take a systems view of a city or country.

The first group describes *models* in which multiple infrastructures are covered, but with a focus on climate change impact and mitigation. Arndt et al. (2011) include effects of flooding on road infrastructure and maintenance, and effects of climate variability on agricultural yield and land loss. Jollands et al. (2007) use a regression model to quantify the possible impacts of climate change on and across water, transport, and energy infrastructures in Hamilton, New Zealand. They find that a disruption of energy supply may disrupt other infrastructures, from traffic signals to water treatment. Mackay and Last (2010) discuss the adaptation costs for the water infrastructure, where the effect on energy consumption is included. Schandl and Turner (2009) describe a process-based model that tests policies for Australia in terms of effects on materials, energy, water use and resulting CO_2 emissions. Suarez et al. (2005) describe an assessment method on the impacts of flooding on interrelated land-use conversion and urban transport.

The second group focuses on *qualitative case studies*. Rozenzweig et al. (2011) analyse the communications, energy, transport, water,

Table 3
Overview of systems covered.

Geographic systems (20)	Systems with (elements of) infrastructures (16)			Other systems (12)	
	Water (7)	Energy (5)	Transport (4)	Environment and models (8)	Buildings (4)
City (12) Country (6) Society (2)	Water/management (3) Water cycle Water resources River Coastal zone	Energy (4) Electricity	Transport (4)	Adaptation models (3) Integrated assessment system (2) Atmosphere (2) Climate	Built environment House Commercial buildings Concrete

Table 4
Overview of different methodologies used.

Qualitative methods (23)	Quantitative methods (23)	Methodology (2)
Review (7)	Modelling (17)	Method development (2)
Qualitative analysis (6)	Optimization (3)	
Description (3)	Integrated assessment (2x)	
Case study (3)	Regression	
Discussion (2)		
Screening		
Adaptive experiments		

and waste infrastructures of New York. Miles et al. (2010) study effects among aspects of agriculture, energy and human health for Washington State. Kirshen et al. (2008) are alone in analysing both impacts on and adaptation strategies for energy, health, transport, and water infrastructures for the Boston metropolitan area, based on qualitative estimates. They consider the possible loss of rail service as a consequence of energy-supply disruption.

4. Discussion and conclusion

Climate change is likely to affect our built infrastructures and, consequently, the way society interacts with these infrastructures. We have reviewed the scientific literature on the adaptation of infrastructures from a socio-technical systems perspective by means of a systematic search, a title-based selection, and an analysis of 48 papers. Our analysis indicates that the research addressing adaptation of infrastructures to climate change is growing, but that there are ample opportunities for maturation of the topic.

The papers we reviewed typically focus on either long-term trajectories or short-term effects that may occur far in the future. What they generally fail to discuss is how changes implemented today will affect adaptation processes over the long term. An example would be the development of an “intelligent” electricity grid to enable the integration of distributed and intermittent generation and improve resiliency in the face of climate change over time.

Governments are now looking into the impacts of climate change on infrastructures and beginning to address the interdependencies between infrastructures. Where interdependencies are discussed, our analysis indicates, the research is focused on general interdependencies within major cities, and does not explicitly deal with the explicit interconnections from a socio-technical perspective. The case of electric mobility (where energy and transport infrastructures meet), for example, provides possibilities for adaptation, but such examples were not (yet) found in the literature reviewed. Additionally, we did not find any policy studies at the national level that discuss the interplay between transport and energy infrastructures. This is remarkable, as these (and other) infrastructures clearly are becoming more and more interdependent.

Although various infrastructure impacts and (to some extent) interdependencies are recognized in the literature, they are primarily presented in qualitative, descriptive terms. Policy makers increasingly need insight into the causalities within and across infrastructures, both in the technical and the social domains. The subsequent step to explore these issues quantitatively and to assess the consequences through modelling is rather limited so far. Recent literature enables such an exploration and more research along these lines should be expected in the coming years.

Where infrastructures are modelled, they are typically not modelled according to the socio-technical paradigm (that is, as physical and social elements that interact in various ways), but on the basis of aggregate system-level parameters. For example, a model might show how road congestion may increase, but an analysis of how people's driving behaviour may also change is lacking. As a consequence, an understanding of how both driving behaviours and weather patterns might affect congestion patterns is also lacking. A further missing step is the explicit simulation modelling of adaptation measures. We believe that a socio-technical systems perspective provides possibilities for describing infrastructure systems, simulating their interconnectedness, and, thus exploring the merits of strategies for adapting our society's backbones to climate change.

Acknowledgements

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Appendix. Overview of results

Table 5
Results of the literature review.

Reference	Time	Methodology	System	Infra as socio-technical system	Focus	Aspects	Interconnected	Quantitative
Arndt et al. (2011)	Long	Integrated assessment	Mozambique	Yes	Landscape, social	Biophysical and economic aspects	Yes	Yes
Belzer et al. (1996)	Long	Modelling	Commercial buildings	No	Landscape, technical	Energy consumption	No	Yes
Brown and Lall (2006)	Medium	Modelling	Water cycle	No	Landscape	Impact of scarcity on national economies	No	Yes
Costello et al. (2009)	Long	Discussion	Society	No	Landscape, social	Health	No	No
Davis et al. (2010)	Long	Modelling	Energy	Yes	Technical	CO_2 emissions	No	Yes
Decicco and Mark (1998)	Long	Model and policy analysis	Transport	Yes	Technical, social	Forecast of energy consumption of transport sector possible policies	No	Yes
Easterling et al. (2000)	Long	Discussion	Atmosphere	No	Landscape, social	biological and social effects	No	No

Table 5 (*continued*)

Reference	Time	Methodology	System	Infra as socio-technical system	Focus	Aspects	Interconnected	Quantitative
Eum and Simonovic (2012)	Short	Modelling	Upper Thames River basin (CN)	No	Landscape	Extreme climate events	No	Yes
Evans (2011)	Long	Adaptive experiments	Urban system	No	Social	Urban governance	No	No
Fankhauser et al. (1999)	Long	Qualitative analysis	Climate change	No	Landscape, social	Adaption strategy for increased flexibility and resilience	No	No
Frederick (1997)	Medium	Description	Water, management	No	Social	Economic, institutional	No	No
Fuglestvedt et al. (2010)	Short	Modelling	Transport	No	Landscape	Metrics	No	Yes
García-Montero et al. (2010)	Long	Screening	Country	Yes	Landscape, technical	Infrastructure plan, biodiversity	No	Yes
Gasper et al. (2011)	Long	Description review	City	No	Landscape, technical	Extreme climate events, health, scarcity	No	No
Greenough et al. (2001)	Long	Review	Country	No	Landscape, technical	Warning systems, disaster management	No	No
Hoffert (2010)	Long	Review	Electricity	No	Landscape, technical	Fossil fuels, technology choice, policy	No	Yes
Hunt and Watkiss (2011)	Long, short	Review	City	No	Landscape, technical	Coast, built environment, energy, health, water	No	No
Jollands et al. (2007)	Long	Regression	City	Yes	Landscape, technical	Water, energy, air, transport	Yes	Yes
Keith et al. (2006)	Long	Integrated assessment	Atmosphere	No	Social, technical	CO_2 capture from the air	No	Yes
Kirshen and Ruth (2004)	Long	Modelling	Boston (US)	Yes	Technical	Energy, health, transport, water	No	No
Kirshen et al. (2008)	Long	Qualitative analysis	Boston urban area	Yes	Technical, social, landscape	Various urban infrastructures	Yes	No
Koetse and Rietveld (2009)	Long	Qualitative analysis	Transport	Yes	Landscape, technical, social	Modalities	No	No
Krol et al. (2006)	Long	Modelling	Water, management	No	Landscape, social	Semi-arid regions	No	Yes
Liu et al. (2007)	Long	Optimization	Energy	No	Technical	Energy systems, polygeneration	No	Yes
Lynch et al. (2004)	Long	Modelling	City	No	Landscape	Ice smelting, extreme winds, storms	No	Yes
Mackay and Last (2010)	Long	Modelling	Water, management	Yes	Landscape, technical, social	Decision support tool for water management	Yes	Yes
Mcmichael and Sari Kovats (2000)	Long	Qualitative analysis	Adaptation models	No	Social landscape	Biological, behavioural and social adaptation strategies	No	No
Miles et al. (2010)	Long	Review	Washington State	Yes	Landscape, social, technical	Effects of climate change scenarios	Yes	No
Molderink et al. (2010)	Short	Optimization	House	Yes	Social, technical	Energy demand profiles	No	Yes
Pearce et al. (2011)	Long	Review	Inuvialuit Settlement Region	No	Social	Food security, health, transport	No	No
Powlson et al. (2005)	Medium	Modelling	UK	No	Landscape, technical	Fossil fuel emissions from agriculture	No	No
Rozenzweig et al. (2011)	Long	Case study	New York	Yes	Landscape, social, technical	Effects of sea level rise and coastal flooding	Yes	No
Ruth et al. (2007)	Medium	Modelling	Hamilton (NZ)	Yes	Technical, social	Water consumption and drinking water supply	No	Yes
Sanden and Azar (2005)	Long	Review	Energy	Yes	Social, technical	Technology, R&D spenditure	No	No
Schandl and Turner (2009)	Long	ASFF model	Australia	Yes	Technical, social	Ematerialization and resource use	Yes	Yes
Scheer (2011)	Long	Review	Energy	No	Technical	CCS	No	No

(*continued on next page*)

Table 5 (*continued*)

Reference	Time	Methodology	System	Infra as socio-technical system	Focus	Aspects	Interconnected	Quantitative
Schwoon (2008)	Long	Modelling	Transport	Yes	Technical	Diffusion fuel cell vehicles	No	Yes
Shen et al. (2011)	No time	Modelling	Integrated assessment	Yes	Technical, social	Recycling	No	Yes
Smith (1997)	Long	Methodology	Adaptation models/ policy	Yes	Landscape, social	Adaptation policies	No	No
Stakhiv (2010)	Long	Case study	Water resources	No	Landscape, social	Management under uncertainty	No	No
Stewart et al. (2011)	Long	Modelling	Concrete	Yes	Landscape, technical	Advanced corrosion	No	Yes
Suarez et al. (2005)	Long	Modelling	Boston (US)	Yes	Landscape, technical	Effects of flooding on transport	Yes	Yes
Thimmapuram et al. (2010)	Short	Agent-based Modelling	Energy	Yes	Technical	Price elasticity of demand	No	Yes
Tol et al. (2003)	Long	Case study	River	Yes	Landscape, social, technical	Management options	No	No
Vellinga and Klein (1993)	Medium	Methodology	Coastal zones	No	Landscape	Vulnerability	No	Yes
Warren et al. (2008)	Long	Modelling	Integrated assessment system	No	Landscape, social	Mitigation of CO_2	No	Yes
Wilby (2007)	Long	Qualitative analysis	Built environment	Yes	Landscape, social, technical	Urban climate change impacts	No	No
Woodcock et al. (2007)	Long	Qualitative analysis	Transport	Yes	Social	Health	No	No
Wuebbles et al. (2010)	Long, short	Review	Chicago (US)	No	Landscape, technical	Temperature, health, precipitation, aquatic ecosystems, energy	No	No

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