



Understanding barriers to decision making in the UK energy-food-water nexus: The added value of interdisciplinary approaches



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ABSTRACT

The nexus represents a multi-dimensional means of scientific enquiry which seeks to describe the complex and non-linear interactions between water, energy, food, with the climate, and further understand wider implications for society. These resources are fundamental for human life but are negatively affected by shocks such as climate change and characterize some of the main challenges for global sustainable development. Given the multidimensional and complex nature of the nexus, a transdisciplinary approach to knowledge development through co-production is needed to timely and effectively inform the decision making processes to build societal resilience to these shocks going beyond the sectorality of current research practice. The paper presents findings from five themed workshops (shocks and hazards, infrastructure, local economy, governance and governments, finance and insurance) with 80 stakeholders from academia, government and industry in the UK to explore the impact of climate and weather shocks across the energy-food-water nexus and barriers to related responses. The research identified key stakeholders' concerns, opportunities and barriers to better inform decision making centred on four themes: communication and collaboration, decision making processes, social and cultural dimensions, and the nature of responses to nexus shocks. We discuss implications of these barriers and how addressing these can better facilitate constructive dialogue and more efficient decision-making in response to nexus shocks.

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1. Introduction

Global sustainable development challenges that the world faces such as climate change, financial and macroeconomic instability, green growth, growing urbanization and income inequality, are deeply connected with energy, food and water resources, or the so-called energy-food-water nexus (WEF, 2011; Smajgl et al., 2016; Biggs et al., 2015). These resources are limited yet fundamental for coupled human-natural systems and are depleting at a rate faster than the planet can replenish (FAO, 2012). Human activities have devastating impacts on ecosystems (Millennium Ecosystem Assessment, 2005) and contribute to global scale challenges such as climate change (Smith et al., 2014) with growing evidence demonstrating negative impacts on socio-economic development affecting years of progress in tackling global poverty and vulnerability (World Bank, 2013). The year 2015 reached an important milestone of average global temperatures reaching 1 °C above pre-industrial times (Met Office, 2015) and the last decade

was characterised by more frequent and disruptive weather events (e.g. typhoon Haiyan, the Philippines and hurricane Katrina, USA), representing 94% of insurance claims for 2015 and costing over \$27 billion (Munich Re, 2016). In addition, increasing uncertainty over energy security and significant volatility in food and energy prices led to increased risk of civil unrest and political instability (Hsiang et al., 2011; Kelley et al., 2015). These have in turn increased social and economic risks of costs of nexus 'shocks' such as flood events, energy blackouts or breadbasket failures (Munich Re, 2012; Hallegatte et al., 2016).

These complex sustainability challenges call for major innovation (Ely et al., 2013; Leach et al., 2012) and reflexive transformation (Stirling, 2014). As a concept, the nexus is supported by a rapidly growing evidence base and a community of practitioners and policy makers, providing a powerful but largely disconnected knowledge base to understand the relationships and trade-offs between the different sectors and disciplines characterising the nexus (Harris and Lyon, 2013; Allan et al., 2015; Stirling, 2015; Kurian et al., 2016; Azapagic, 2015). These have, until recently been viewed as separate and distinct. Researchers, practitioners and policy makers working in and across the nexus have sought to

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characterize, understand and eliminate trade-offs and tensions across and between these sectors (Rasul, 2015; Rasul and Sharma, 2015), whilst simultaneously highlighting opportunities, synergies and common goals (e.g. the UK's EPSRC Sandpit water-energy-food nexus project and the EU's Horizon 2020 Research and Innovation Actions on Societal Challenges). The reason for this is that the use of energy, food and water, and their management, is at the heart of human development and economic activity (Hoff, 2011). The risks associated with the mis-management of these resources has created a substantial social debate under a variety of frames such as sustainable development, sustainability, green economy, natural capital, environmental governance and ecosystem services. The nexus is the latest framing around these issues and provides a natural frame for rethinking sustainability as a complex adaptive system for analysing problems which can be approached more effectively when considered holistically (Yumkella and Yillia, 2015). In this regard, the nexus contributes to the discussion about the identification of more effective measures of economic success to design resilient business strategies (Reynolds et al., 2014), and thus the need to go beyond GDP as an indicator of economic activity (Stiglitz et al., 2010) to account for negative and time dependant externalities of human actions on ecosystems.

We consider nexus *shocks* as low probability, low frequency but high impact events (in terms of physical and economic losses) that span energy, water and food systems (Endo et al., 2015; Howarth, 2016). They impact multiple actors within and across country boundaries at scales that make them complex to understand and to address with implications for integration into decision making processes (Hussey and Pittock, 2012). Moreover, the interlinked nature of the nexus with finance, the economy, policy governance and demographics implies a variety of sources of shocks to the nexus. These can be either endogenous (e.g. the effects of climate change risk on GDP, demographic trends and migration) and exogenous (e.g. financial instability and market bubbles), where

correlation of shocks occurring in the same and/or in several dimensions simultaneously increases the risk of stranded assets for both private and public investors and uncertainty about investors' portfolio allocation (Monasterolo and Battiston, 2015).

The most recent catastrophic events and their costs in terms of GDP and human lives (e.g. Hurricane Katrina) show that no sector is immune from these shocks. In an extremely globalized world, single events may induce systemic, cascading effects which can impact several sectors, processes, resources instrumental and fundamental for human development. Thus, addressing this nexus challenge means ensuring timely access to key resources such as water, food and energy to a global population expected to reach 9 billion in 2050, which itself has changing consumption patterns and will reside predominantly in urban areas (UNDP, 2014). Similarly, a methodological framework to analyse the nexus in its multidimensionality accounting for feedback loops and cascading effects is missing despite recent attempts to go beyond the sectorality of research. Therefore, in this paper we explore the application of our findings of a newly developed methodology to study nexus shocks and derive implications for policy making.

2. Inside the water-energy-food nexus

The nexus is defined by a number of elements (Table 1) and can be described as both (i) a descriptive account of interactions and interdependencies between the elements that define it, as well as (ii) a process that enables and supports transition and transformation across sectors and stakeholders. The nexus allows for a more holistic understanding of (un)intended consequences of policies, technologies and practices whilst highlighting areas of opportunity for further exploration. Nexus thinking represents a multi-dimensional means of scientific enquiry which seeks to describe the complex and non-linear interactions between water, energy and food systems, with the climate, to support

Table 1
Key elements that define the energy-food-water nexus.

Theme	Characteristics
Uncertainty	Uncertainty about mutual impacts Policy uncertainty in terms of building resilience Uncertainty around societal changes that influence the nexus
Connectivity	Interconnection and network of relations Time and path dependency of responses
Risk	Interlinkages Complexity Potential systemic effect
Impacts	Potential cascading effect (through society or across the nexus) Cascading, amplifying, nullifying impacts combining discrete but defined sectors
Nonlinearity	A simple system is a process where its components, their interactions and outcomes are known and can be defined (for example where the process starts, how it works and where it ends). Complex systems consist of multiple interacting components, where the relationships between the different variables is not linear. They are usually characterised by "a large number of uncoordinated interactions between [its] elements" (Ladyman et al., 2013) which contribute determining emerging behaviours among heterogeneous agents. The order in which these interactions occur is neither completely casual (random) nor follows a set schedule (Holland, 1995, 1998).
Feedbacks	A feedback can be defined as the reaction from a component or variable of the system that follows an action from a different component of the same system. Negative feedbacks have a balancing effect between two variables or components of the system and usually represent an inverse relationship between them (the action and the reaction move in opposite directions). Positive feedbacks have a reinforcing, amplifying effect between two variables or components of the system and usually represent a positive relationship between them (Forrester, 1961; Sterman, 2000; Mollona, 2008).
Robustness and flexibility	In complex systems, the order is said to be robust, even if the system is perturbed by endogenous forces, it still remains stable due to its fixed structure. A centrally controlled system is more exposed to internal perturbations.
Emergence	Emergent patterns are characteristics or behaviours resulting from a complex system that could not be captured by merely studying its single components in isolation (Holland, 1995, 1998).
Hierarchical organisation	A complex system is usually formed by several different sub-systems and components all interacting one with the others. These are organised in a hierarchical structure where the complex system is at the top and the subsystems are at the bottom.
Independent system	The nexus exists in its own self without the need for human intervention. In fact, human intervention (social) has destabilised complex relationships among different variables in the nexus with social responses aiming to stabilise it
Dependency	Because the environment abides by biological and physical mechanisms, the nexus is characterised by concepts of delay and chaotic behaviours

understanding of their wider implications for society (Smajgl et al., 2016). The concept of the energy-food-water nexus captures interconnections, dependencies and linkages between production and use of energy, food and water resources. Agriculture provides a useful example of this, according to the FAO (2014), 70% of total global freshwater withdrawals come from agriculture and are used for (i) food production, (ii) forestry, (iii) fisheries, and (iv) energy production. However, a significant amount of water is wasted in agriculture, due to outdated irrigation systems, farmers' low understanding of water-saving technologies and water intensive crops grown in water stressed areas (e.g. almonds in California, cotton and sugar beet in the Caribbean). Simultaneously, the food supply chain uses close to 30% of total energy consumed globally, and energy represents 30–40% of production costs for farms through fertilizers, machinery, food distribution systems and in order to extract and pump water from aquifers in water stressed areas.

In terms of understanding causality and impacts, decision makers have a tendency to focus on short term and sectoral bounded problems/benefits placing less emphasis on long term implications for the system as a whole (Sterman, 2012). Consequently, sector-bound decisions lacking diverse participation mechanisms (Ilin and Varga, 2015) are often 'compartmentalised' (Sharmina et al., 2016) and taken with little consideration for the effects of those decisions on other sectors leading to rebound, cascading or other negative effects, mainly due to the mutual interdependence of these (Sterman, 2006) with implications for consistencies of decision making processes (Howells et al., 2015). This raises questions on the effectiveness of those working at the science-policy interface (Sutherland et al., 2012) and can result in undesired performance patterns both for individual sectors as well as the human-natural system, eventually leading to the emergence of systemic risk and its spread along the system.

The nexus is characterised by high levels of interconnectivity and uncertainty and consequently benefits from its unbounded definition whilst being guided by its scope of approach and application when considering a specific situation or topic. The way in which to organize its governance remains an open issue, particularly when considering complexities around the variety and forms of data used to inform nexus related decision making (Gilbert and Bullock, 2014). Questions on how to structure its governance remain unanswered but constructive research on tools to compare approaches (Mannschatz et al., 2016) and how regional and local challenges can be better addressed when considered from larger or broader perspectives (Scott et al., 2011) provide encouraging momentum into how to better inform decision making around nexus challenges. Stein et al. (2014) define a strategic action perspective to build the foundation of nexus governance, acknowledging that (i) nexus challenges are intrinsically related to the perceptions, interests, and practices of actors associated with a nexus, (ii) there is the need to understand nexus governance by looking at the relationships between actors/issues and their networks across multiple domains, and (iii) the need for understanding the existing governance arrangements in which the nexus approach will be introduced. Stirling (2015) explores this and discusses the slow change that characterizes decision making dynamics and the formation of evidence based policies, moving from a 'vertical' model of expert-driven analysis implemented by orderly top-down procedures to more horizontally distributed forms implemented through bottom-up action through social mobilisation.

The impact of climate change on access to nexus resources in the next decade is likely to be predominantly negative (US Environmental Protection Agency, 2010; Smith et al., 2014; Lloyds, 2015) with a range of possible issues likely to occur (e.g. ecosystems and human systems under stress, access to key resources and wellbeing: Asian

Development Bank (2013), Monasterolo and Battiston (2015)). Increasing difficulty to access nexus resources has multiple and multidimensional consequences such as uncertainty with regards to future economic growth, spread of risk on financial markets as a consequence of stranded assets, volatility of commodity prices, increasing inequality and worsening living conditions, food security in vulnerable regions (World Bank, 2012), and international political instability (e.g. the Arab Spring: Lagi et al., 2012; Nomura, 2012). Adopting a nexus lens enables a flexible approach through which the system's efficiency and productivity are considered as opposed to individual sector's productivity in isolation. It is complex, and lies in the interconnection of different sectors/subjects/resources themselves characterised by complex behaviours because of the interconnectedness between their parts. As a dynamic complex system, it has boundaries and is driven and framed by its non-linearity, feedback system, spontaneity, robustness (Waldrop, 1992; Ladyman et al., 2013).

Academic research attempts to constrain sustainability research within specific and well-defined research areas, adopting existing area-specific approaches which have historically misaligned with decision maker's needs and processes (Viner and Howarth, 2014). In addition, a thorough critical assessment of what a transdisciplinary approach is – its characteristics, role, knowledge and tools needed for its implementation – is missing alongside a comprehensive assessment of how and what it can contribute to research on decision making. Harris et al. (2014) defined the requirements of a transdisciplinary approach for nexus analysis reviewing literature (76 publications) on *trans-disciplinary* research but focusing only on the challenges to implementation. In particular, they identified the associated theoretical (framing problems), methodological (different conceptions of proof) and practical challenges (communication, collaboration and trust across groups of actors belonging to different disciplines) for nexus analysis. For academia, they found that a key challenge relates to the need to embrace multidimensional knowledge, to adapt the method of interaction to account for transdisciplinary team members (e.g., defining a new language, negotiate, accept the different logics and values, redefine the power balances among disciplines and among scientists and lay practitioners), an advantage to define the nexus. They found both common approaches and challenges to the current business-as-usual, sector based scientific production in academia.

Building on the findings and recommendations of recent literature, this paper attempts to address part of this gap and provides an overview of a transdisciplinary approach of analysis for understanding nexus shocks related to climate change risks, developing a how-to framework for the analysis of the resource nexus.

3. Methodology

Drawing on findings from an ESRC-funded project (reference G1334-26) which brought together participants from academia, industry, policy and non-governmental organisations in five workshops, this paper innovatively addresses how to better inform decision making in the context of shocks to the energy-food-water nexus. By building on the results of the workshops (Howarth et al., 2015; Howarth and Jones, 2016) this paper presents findings and discusses the role of transdisciplinary approaches in the context of the following themes: (i) assessing shocks to the energy-food-water nexus and their interconnectedness with climate change, (ii) exploring best practice and lessons learned in to provide accessible and relevant information to policy makers, and (iii) identifying obstacles preventing researchers and scholars from developing more transdisciplinary approaches to analyse nexus shocks.

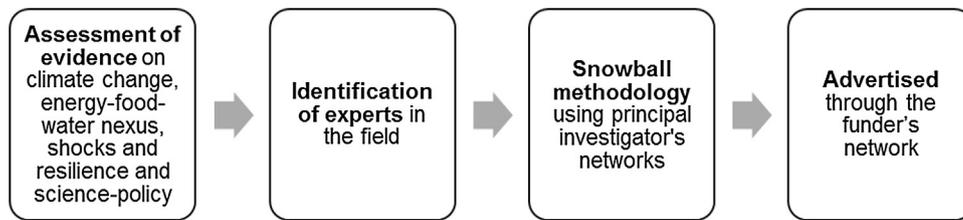


Fig. 1. Participant selection process.

A knowledge co-production approach was adopted where expertise from across disciplines and fields was represented by the diversity of individuals invited to take part in the workshops. Using this approach, a preliminary focus group was held to refine the method of the workshops, identify the key themes to explore and assess suitable participants (Howarth et al., 2015). The premise for adopting models of co-production across sectors is useful for capturing different approaches to knowledge production by promoting stakeholders' engagement and commitment. We adopted a combined top-down and bottom-up approach to enable the co-design of knowledge and solutions to nexus risks by providing the space for multiple actors involved in the process to share their sector specific expertise, actively engage and challenge each other's views, cultures and contributions to participate in a constructive dialogue. Each workshop covered one the following themes as defined in the preliminary focus group: (i) Predicting shocks and hazards (PSH), (ii) Transmission and mitigation of nexus risks through infrastructure (I), (iii) Local economy responses to shocks (LE), (iv) Insurance and finance for resilience (FI), and (v) Governance, governments and shocks (GG). Five half day workshops were held in London, UK between September and October 2015 with $n=78$ individuals (Fig. 1 and Table 2) from three pre-defined categories: (i) academic, (ii) practitioner (directly involved in implementation of climate-related solutions or decision making processes on the ground) and (iii) policy communities (involved in formulating policies and decisions on climate change and nexus related issues). Participants were approached based on their knowledge, expertise and experience of decision-making on climate change and nexus related issues, for example decision-making processes directly related to or with implications for energy, food and/or water interactions. These were identified using an assessment of the literature and of UK institutions and individuals in positions that fit one of the aforementioned categories, approached via the project contacts and networks. Participants were invited to one or more of the workshops with sufficient notice to maximise the chances of their availability, on occasions where specific invitees were unable to attend, they were asked to send a substitute from their organisation.

The workshops explored in the first instance the reasons and consequences of persisting sectorality of current scientific research, which fails to analyse the systemic and

multidimensional characteristics of risk linked to the nexus challenges, and in providing timely, transparent and accessible results to non-academics and policy makers. Secondly, we explored the range of involvement of stakeholders in defining the issues at stake for building resilience to nexus shocks both at the sector and societal level, and identifying effective solutions. Finally, we assessed the limited understanding of the role of governance on policy implementation, and the multidimensional incentives involved in the policy cycle. Each workshop adopted a semi-structured approach, with a structure piloted and refined beforehand. Workshops lasted half a day each with discussions recorded in written format with consent from all participants. The workshops were conducted under Chatham House rule to encourage open constructive dialogue on the key themes discussed. Discussions were analysed using thematic analysis and were drafted as a workshop summary which was then shared with participants to review and comment on it as part of the internal review process.

4. Results and findings

Each workshop began with a rapid exercise to assess and discuss participant's experience of decision-making related to nexus shocks. Participants represented UK organisations such as SMEs, scientific organisations, non-governmental organisations, international consultancies, government departments, universities, private sector organisations, the finance sector with nexus related shocks ranging from infrastructure resilience, emergency service responses, design and implementation of low-carbon technologies, urban re-generation, energy transitions and water-food supply resilience. While the sample size ($n=78$) and geographic representation of the participants (i.e. United Kingdom) necessitates caveats with regards to the representation of our findings and suggests the role of further research with larger sample sizes and representation from different geographical and sectoral populations, findings from these workshops nonetheless provide valuable insights into decision making under nexus shock scenarios.

Analysis of workshop discussions identified four dominant themes that emerged as barriers to decision-making in the context of nexus shocks, across each of the workshops: communication and collaboration, decision making processes, social and cultural dimensions, and the nature of responses to nexus shocks. Analysis and discussion of each theme, with reference to each workshop,¹ is presented below and summarised in Table 3.

4.1. Communication and collaboration

Communication and collaboration are seen as vital to ensure the most appropriate and robust evidence informs decision makers

Table 2
Workshop participants.

Workshop	Participant type			Total
	Academic	Practitioner	Policy	
Predicting shocks and hazards (PSH)	7	4	4	15
Infrastructure (I)	6	6	3	15
Local economy (LE)	1	7	3	11
Finance and insurance (FI)	4	14	2	20
Governance and governments (GG)	7	5	5	17
Total	25	36	17	78

¹ The following codes are used to identify the source of discussion: PSH: Predicting shocks and hazards; I: Infrastructure; LE: Local economy; FI: Finance and insurance; GG: Governance and governments

at all levels within the context of a nexus shock. Whilst we have described above the inter-disciplinarity of the nexus and the complexities around decision making, issues related to communication arise as a result of its cross-sectoral and transdisciplinary nature. For example collaboration between actors across sectors impacted by nexus shocks can lead to clashes in languages and lexicons as well as skillsets and expertise further exacerbating barriers that may emerge in the communication process (PSH). In addition, evidence production was a key sub theme which emerged due to the varying levels of data produced and the implications this can have such as tunnel vision, biased decision making, failure to consider alternative data and forms of evidence (PSH). Evidence produced in the context of a nexus shock is often generated in immediate response to the shock taking place leading to insufficient 'foresight' thinking on the immediate impacts of the shock, particularly when this is a gradual or cascading shock within a system. This then was discussed by participants as having implications for better informing responses and how these could be adequately used by decision makers (GG). The range of stakeholders participating in the workshops shed light on the conflicting systems and processes which exist, and the implications of loss of historical memory of decision making processes as an example. This was discussed particularly in the context of infrastructure resilience and systems in place to respond to shocks where loss of expertise as well as gaps in training and skills development, for example in policy organisations with high turnover, leads to a cycle of knowledge production with minimal consideration for the importance of capturing the development and evolution of this knowledge and lessons learnt (I).

Concerns around the complexities with communicating risk and levels of uncertainty in evidence emerged strongly, particularly when decision makers are looking for clear advice as opposed to a range of probabilities (PSH) and they themselves communicate risks through their own established processes (GG). This was felt to be the case for infrastructure where the complexities of how shocks impact the built environment are unpredictable. When combined with a lack of understanding of future societal needs and the uncertainty surrounding the resilience of infrastructure to these shocks (I), communication was perceived as an exacerbator of negative impacts with increased vulnerability of the system at the core (I). This mismatch between knowledge producers understanding of risk, uncertainty and complexity emerged particularly when discussing the national, international and local contexts. The multiple voices and actors that interact in response to a nexus shock, for example at the local level, can lead to a convoluted and confused understanding of risks of nexus shocks in general and the risks of this locally (LE).

The process through which communication channels are designed to aid decision making processes can themselves create complexities. For example the timing and accessibility of communication is vital to manage flows of information to different stakeholders and specific times and avoid saturation (PSH). Lack of communication and transparency can lead to challenges in bringing together appropriate stakeholders to co-create decisions with full consideration of implications on other sectors and stakeholders. This is further exacerbated by a self-reinforcing process by which this lack of communication affects trusted relationships and reduces confidence in judgement-based decision making (GG). Awareness of the flow of information can be severely affected by disruption to communication channels during and after a shock where a support infrastructure highly dependent upon by stakeholders and the public can be ineffective or unusable during and/or after a shock (PSH). This over-dependency can have unexpected consequences going beyond expected infrastructure, resource or decision making processes. Whilst increasingly used to communicate around a range of issues, and emerging as useful to

inform decision making, social media tools were also discussed by participants with mixed views on their use as they were felt to at times over-complicate processes for managing responses and actors involved in that response (GG). Similarly it was felt that the abundance of information discussed earlier is further exacerbated by the medium of communication such as social and conventional media processes leading to desensitised audiences on the issue (LE).

A general misunderstanding of the knowledge needs of different audiences is particularly evidenced around the local level where generalised messages on shocks tailored to a regional, national or international context may be inadequate locally particularly if it fails to fully consider this context (LE). This was also the case in considering the financial dimensions of nexus shocks where low financial literacy and low understanding of societal current and future needs exacerbated perceptions of the issue (FI). The saturation of the information space around one issue was felt to often lead to reductions in trust of decision makers. Wariness of repeated messages added to this lack of trust towards decision-makers and those informing them (LE) which could potentially lead to reputational risks (PSH) with implications for subsequent decision making processes if audience are unable to trust the messenger or the decision maker. This issue around trust was further convoluted with confidentiality issues where, in the private sector for example, organisations may be reluctant to share data (FI), calling for better mechanisms to securely share important data produced and used by stakeholder groups.

4.2. Decision making processes

The role of responsibility emerged strongly in the workshops with discussions on whose responsibility it is to tackle whole or components of the decision making process (GG) and leader's willingness to accept responsibility for decisions made (or to be made). This is particularly true where there is a lack of clarity over who owns the problem or the decision (LE) and action taken can have implications for the future and local action can have global impacts (PSH). Depending on how the shock will have impacted different stakeholders, a willingness to accept and take responsibility will vary particularly when a solution and benefits of this response may lie outside an asset or decision owner (PSH). This was particularly felt in terms of determining whose responsibility it is to pay for the cost of response and building resilience (FI) with automatic assumptions that the insurance industry should take significant responsibility combined with increasing focus on the political community play an active role in managing other costs.

Conflicting timescales between research and policy combined with the social dimensions of decision making and the need for researchers to achieve consensus before they can contribute to decision making can exacerbate responses to shocks and cause existing decision making processes to become redundant (I). The role of lessons learnt and a general failure (although this is improving) to capture lessons learnt from nexus shocks and responses emerged strongly. In particular, concerns around implications of not having systems in place to capture these lessons during and after the shock, how this could inform thinking in future shocks and how these lessons learnt could then be transferred and applied to other sectors and scales (GG). Framing of a risk, the language used, levels of uncertainty considered and the geographical impact of a shock affect the type of response, its implementation and various leadership roles within it (FI). In the context of nexus shocks, responses are often reactive rather than proactive (PSH) leading to increased risk of passive, panic or irrational responses (LE). However a low acceptance of ownership and benefits of the 'victims' of a shock, such as

infrastructure, can lead to a collection of resilient assets whilst a weak resilient system (I).

4.3. Social dimension and culture

The complexities of the nexus mean its resources are interlinked, used and affected by different stakeholders across different sectors, each characterised by different cultures, behaviours, priorities and processes (LE, PSH). Impacts from nexus shocks and the meaning of response and resilience is subject to interpretation, can have different meanings in different contexts and itself is informed by failure (PSH). A question emerged on whether decision makers (including the public) need to understand the complexities of the shock, its interaction with systems and related risks, how this differs in urban and rural settings (LE) or whether a fair understanding of risk alone is required (PSH). This conflicts somewhat to scientists' perceptions of the need for end users to be told about many aspects of the science to inform their decision making. In a related manner the role of social representations in decision making processes is increasing with the growing presence and role of social media in providing a direct route to decision makers (GG).

The notion of judgement based decision making emerged by which decision makers assess the evidence presented, often with a preoccupation for their legacy (GG), preference for one type or source over another (LE) and where a dichotomy of choices (i.e. make a certain decision versus not making it) exists, rest on their judgement to inform their decisions (PSH). The cost of inaction versus the price of adaptation (LE) then emerges with decisions varying according to the evidence available, context, public support and considerations for the varying interests and values of stakeholders (GG).

Whilst nexus shocks have significant societal impacts these are at times indirect and challenging to perceive. For example the lack of understanding of what infrastructure provides to society (i.e. a 'social contract') until it fails, means its services are underestimated (e.g. uninterrupted provision of resources such as energy food water to society) until these are disrupted by a shock (I). Similarly impacts of shocks are felt differently at the local level compared to the national (and for example the urban versus rural contexts) hence scaling up, transferability and shared knowledge on responses and lessons learnt faces unavoidable challenges (LE). These layers of complexities can distract attention away from root causes of the issues where symptoms and impacts are addressed as responsive priority rather than creating space for active retrospective reflection on the wider system within which a nexus shock occurs and it's resulting cascading effects (GG). Consequently in addition to demand side responses to nexus shocks, demand for access to energy food water resources and services they provide must consequently be adjusted (I).

4.4. Response to shock

The production of scientific evidence used to inform decision making in response to nexus shocks is imprecise, fraught with uncertainties and constantly evolving (PSH). This means that the nexus shocks at the local scale for example can be granular and location specific both in terms of impacts and exacerbating causes meaning that allocation of resources can be uncertain and increase vulnerabilities (PSH).

There are numerous challenges associated with costing the benefits of resilience to nexus shocks notably who pays for the cost (LE), the interdependencies between assets leading to cascading effects (FI) and that those bearing the cost of resilience to not always realise this has for the short and

long terms (I). Capacity and ability to adapt to impacts and different levels of risk carries at all scales (FI) so the question of who pays for resilience and at what stage is one which often remains uncertain (GG). This further enhances complexities around insurance in vulnerable communities (FI) and justifying ownership of one or more risks when these are long term, distant and potentially costly (GG).

Shocks by their nature may require quick-thinking and the implementation of creative and innovative ideas however strict requirements and guidelines, and challenges of having discussions at the local level and global scale (GG), can create additional barriers and a lack of clarity and availability of resources to help manage these shocks (LE). There appears to be limited ongoing discussion at the national level of what ultimately wants to be achieved (GG) and hence how this is affected by shocks. When considering how climate change as an exacerbator of nexus shocks is incorporated into insurance on a yearly basis (and renegotiated within that timescale), this narrows the vision for change within that sector (FI). This may conflict for example with local or national government timescales, often reactive and influenced by the electorate (GG), for implementation of solutions and investment into resilience programs. Complexities in different regulatory systems and short returns on investment (I) further exacerbate nexus shocks and responses to them.

4.5. Discussion

Table 3 categorises the main barriers to decision making in the energy-water-food nexus identified in the workshops. Building dialogue among different sectors is considered fundamental, with information and communication emerging both as a barrier and an opportunity to build resilience to nexus shocks. The lack of timing and access to transparent and targeted information prevents cross-sectoral collaboration, as well as not accounting for different languages and stakeholder appetites, which is considered fundamental to build trust among stakeholders. Facing communication challenges is required to minimise miscommunication, and better understand future societal needs whilst consulting historical experience. This would contribute to overcoming several current barriers such as the lack of community understanding of risk, people's desensitisation by information networks, and lack of trust in decision makers and those informing them. The barriers to access sector specific information prevent both the general public and sector specialists from understanding specific concepts linked to nexus shocks, calling for a greater role of education to sustainability and resilience.

Table 3
Summary of workshop findings by theme.

Theme	Sub theme
Communication and collaboration	Evidence production
	Process
	Communication
	Audience needs
Decision making processes	Trust
	Conventional and social media
	Response
	Responsibility
Social and cultural dimensions	Informing and lessons
	Culture
	Judgement versus evidence
Nature of responses to shocks	Disconnection from the issue
	Uncertainty of science
	Cost of resilience
	Complexities of processes

Access to and understanding of information is heavily mediated by the social and cultural dimension of decision making processes, with a lack of stakeholders' awareness undermining community trust and creating bottlenecks in nexus shocks responses. Inclusion, intended both as physical (rural-urban integration) and societal (engagement of civil society) emerges both as an opportunity and barrier, with the need to consider different interests and values of all stakeholders. Framing nexus risks requires accounting for the effect of different geography, language and time, identifying key social infrastructures to be reinforced for building resilience by learning from the previous lessons across sectors and from international experiences.

The need to move from the current reactive to a proactive decision making process emerges strongly, with a necessity to embrace a foreseeing attitude to future nexus shocks and understand the importance of local action for global impacts. The lack of a holistic view and identification of ownership (i.e. whose responsibility it is to respond to different shocks) and the presence of conflicting timescales of research, business activity and politics present a barrier to effective decision making to nexus shocks. In the long term, coordinated policy programs consistent with local goals play an important role in the identification of key social infrastructures to reinforce resilience building through a participative approach to decision making. These elements influence the nature of responses to shocks among stakeholders groups and determine imbalances, with those bearing costs of resilience not always realising its long term value. Finally, the negative impacts of beaurocratisation constitute a barrier to creative and innovative thinking, increasing the timing of responses and creating confusion in regards to who pays and who benefits from the response.

The four themes allowed us to compartmentalize nexus knowledge, discuss the barriers that emerged and compare the results obtained in the workshops. Whilst the research presented in this paper is based on workshops conducted in the UK, and consequently findings are more applicable to this context, this exercise proved effective to identify best practices and lessons learned providing a useful basis to explore transferability and scalability of results to other contexts (E.g. different scales, different contexts).

5. Discussion and conclusion

The water-energy-food nexus displays a number of complexities, opportunities and challenges which are inter-disciplinary, cross-cutting and multi-sectoral. These complexities are not solely limited to one sector, which are intrinsically linked due to the dependencies between energy, food, water resources to provide basic resources to further human and economic growth. Consequently, interactions and shocks to one of these resources will inevitable impact one or more other sector. A nexus approach enables the capitalisation of knowledge and the sharing of skills and expertise to build innovative solutions to complex interlinked nexus challenges.

This paper provides an innovative approach to the analysis of a key issue of decision making in response to shocks to the energy-food-water nexus. In particular, we showed why understanding the characteristics of the nexus is important to develop measures able to build resilience to nexus shocks thus tackling risk. Given the complexity, non-linearity, space and time dependency of the shocks which may generate in one area of the nexus and trickle down with a cascade effect on the others, eventually affecting other linked dimensions such as finance and real economy, there is a need to move away from current sector-based approaches to knowledge development and solution creation and develop a transdisciplinary approach of analysis.

We presented analysis of data from workshops held the UK obtained applying a participatory, bottom up interdisciplinary approach to knowledge creation developed by working with different stakeholders in the field of business and finance, knowledge production and policy making. We have identified important barriers to the development and application of a transdisciplinary approach, as expressed by stakeholders from multiple sectors, to understand nexus shocks and support policy responses. In particular, what has emerged is that a transdisciplinary approach of assessment and analysis requires active engagement of stakeholders from different sectors in all the phases of knowledge development to acquire a clearer picture of their needs and expertise in the decision making process. This would enable a transition beyond sector-based knowledge on the different yet interlinked dimensions which contribute to shape the nexus. The adoption and implementation of such an approach are complex due to social and practice limitations that are area-specific and common to the fields of science involved. This includes the rules which characterize knowledge development, increased specificity of education and researchers' specialization, lack of return in terms of visibility opportunities such as publishing in top journals, funding applications to public and private bodies, and career development. In this regard, the value added of transdisciplinary approaches to knowledge production helps overcome gaps in the research-policy interface. The application of a transdisciplinary approach to knowledge co-production, as adopted in this research, contributes to identifying a cost and time-effective framework for the analysis of climate risk interaction with the resource nexus across 4 identified themes: Communication and collaboration, Decision making processes, Social and cultural dimensions, Nature of responses to shocks.

We have derived recommendations on how to better inform decision makers and the research community about the challenges of nexus research as well as develop a scalable approach to transdisciplinary analysis of sustainability challenges. In addition we discussed the implications of the findings from this research in the broader context of transdisciplinary research. Whilst we provide only a snapshot in this complex area, and we acknowledge that our findings are drawn from a UK context, these provide valuable insights into cross-sectoral barriers to nexus shocks decision-making processes. We call for further research building on our findings, into the extrapolation and wider transferability of our results to other international contexts, sectors and disciplinary perspectives. Whilst we explore the implications of nexus shocks in the UK, as described earlier in the paper, energy-food-water nexus issues have broader instigating factors with implications for the international context. Understanding of intricate processes at the national and regional level are important and provide a deeper understanding and snapshot of complicated decision making processes within that scope. We therefore call for more work to explore our findings with particular focus on the following areas: (i) approaches to sustainability research management in terms of formation, coordination and integration of researchers coming from different scientific fields of analysis; (ii) the role of transparency, trust and accountability within research teams; (iii) the role of top journals and editors, who may lack appropriate metrics to assess the quality of papers based on a transdisciplinary research approaches (see [Rafols et al., 2012](#)); and (iv) the delay in public and private funding to research on the nexus (such as the EU Horizon programs).

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