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The potential impact of Brexit on the energy, water and food nexus in the UK: A fuzzy cognitive mapping approach

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HIGHLIGHTS

- Coupled cognitive model captures the complexity of the UK Energy-Water-Food Nexus.
- GDP impacts on Energy Demand, whereas Water and Food depend on UK population size.
- Less integrated Brexit scenarios have threefold larger magnitude of predicted changes.
- Whilst dependant on choice of experts, the approach is attractive for Nexus mapping.

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ABSTRACT

Energy is one of the cornerstones essential for human life, along with other services such as water and food. Understanding how the different services in the energy-water-food (EWF) nexus interact and are perceived by different actors is key to achieving sustainability. In this paper, we derive a model of the EWF nexus using fuzzy cognitive mapping (FCM). Data were collected in a two-step approach from workshops with researchers and stakeholders involved in the three focal sectors. Four FCMs were developed; one for each of the EWF sectors, and one for the interactions that create the nexus between EWF. The FCM represents the combined views of the groups who participated in the workshops, the importance and limitations of which is discussed. To demonstrate its effectiveness, the aggregated FCM was applied to predict the impacts on the EWF nexus of four scenarios under which the United Kingdom would depart from the European Union (i.e. Brexit). The FCM indicated that energy-related concepts had the largest influence on the EWF nexus and that EWF demand will decrease most under a 'hard-Brexit' scenario. The demand for energy was shown to decline relatively less than other services and was strongly associated with gross domestic product (GDP), whereas UK population size had a stronger effect on water and food demand. Overall, we found a threefold change across all concepts in scenarios without freedom of movement, contribution to the EU budget, and increased policy devolution to the UK.

1. Introduction

"*Today the network of relationships linking the human race to itself and to the rest of the biosphere is so complex that all aspects affect all others to an extraordinary degree. Someone should be studying the whole system, however crudely that has to be done, because no gluing together of partial studies of a complex non-linear system can give a good idea of the behaviour of the whole.*" Nobel Prize winner Murray Gell-Mann made this statement at an International Society for the Systems Sciences (ISSS) seminar in 1997 [1]. Around the same time, the term 'nexus' started to be used to describe the interconnections between spheres of energy, water and food [2], but then fell out of favour until the second decade of the 21st century. Interest has grown rapidly since then (e.g. [3–5]), especially from the perspective of an environmental trilemma in managing the connections among these three sectors [6–8].

1.1. The energy, water and food nexus and its relevance to the UK

Energy and food production, as well as a secure supply of clean and available freshwater, are all vital to human survival. Yet, the energy,

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food, and domestic water sectors are intricately connected in ways that often lead to intense and undesirable competition for resources. For example, the consumption of water in the life-cycle of energy production can limit its availability for domestic uses such as drinking and sanitation [9]. Such competition amongst energy, water, and food may only be exacerbated by future climate change, economic development, and a growing human population [10]. van Vliet et al. [11] recently predicted that climate-driven changes in global water resources could reduce the usable capacity of most hydropower and thermoelectric power plants, which collectively generate 98% of the world's present-day energy. Furthermore, agriculture, already the largest user of freshwater in many countries, will also increasingly compete with the energy sector for available water, further threatening our potential to sustain human demands for energy, water, and food [12].

A better understanding of the interdependencies - or the nexus - amongst energy, water, and food can help align policies and governance across sectors and scales to deliver a sustainable future [10,13]. Explicit analyses of the energy-water-food (EWF) nexus, however, are rare. One approach is life cycle or material flow analysis [14–16], while another involves more integrated modelling of the dynamics of the energy, water, and food systems [3,17,18]. Here we describe an alternative and new approach aimed at developing a model of the linked 'nexus' domains of EWF and the environment using fuzzy cognitive mapping (FCM). Our aim was to capture the impact of policy changes on the connections between the component parts of the EWF nexus. We focused on parameterising this model in the United Kingdom (UK) and then tested it with different scenarios of governance change. These scenarios were centred on the possible consequences of the UK's departure from the European Union (EU), commonly known as Brexit. Policy, sourcing, and pricing of energy, water, and food in the UK are currently influenced by membership of the EU through access to free trade, subsidies, legislation, and membership of the internal energy market; all of which will see changes following the negotiations for a UK exit from the EU. These changes will, in turn, impact the demand for energy, water and food within the UK. To date, there has been very little analysis of the potential impact on the system as a whole, or into the connectivity of energy, food and water services.

The analyses reported here address the following research questions:

- What do experts and stakeholders from different disciplinary backgrounds perceive to be the influences on and relationships among food, water and energy demand in the UK?
- Based on the "cognitive system model" of these experts, how does the demand for food, water and energy change as the UK leaves the EU?
- To what extent are changes in food, water and energy demand governed by the nature of the future relationship between the UK and the EU?

Our approach was first to capture information from different stakeholders in workshops that ran during November and December 2015 and use these to model the EWF nexus in the UK. FCM [19–21] is widely used for developing an understanding of how components of a system interact in situations where complex interdependencies and feedbacks are thought to exist, but where quantitative and empirically-tested information about these interactions is currently unavailable or difficult to obtain, especially in a short timeframe. Broadly, FCM aims to encapsulate the qualitative knowledge of expert participants to construct a simple systems dynamics model of a specific issue [20]. The resulting output can be used for projection or scenario testing purposes, and to facilitate further discussion and interaction within or with a stakeholder group [20]. We then used expert opinion to demonstrate how scenarios (e.g. [22,23]), in our case centred on Brexit, can be constructed and used within FCM to map policy impacts across the different EWF dimensions.

1.2. Exploring changes in the energy-water-food nexus through Brexit

Brexit provides a particularly useful case study for demonstrating the potential of FCM to model changes in the EWF nexus. The UK has been a member of the EU, and its predecessor (the European Economic Community), since 1973. However, the membership has always generated a degree of discomfort within sections of the UK. In January 2013, against the backdrop of a political party split on EU membership, and the rise of a single issue party, the UK Independence Party (UKIP), then Prime Minister David Cameron pledged that if the Conservative Party were to win the 2015 General Election the government would call a Referendum with one simple question, "should the UK remain a member of the European Union (EU)?". The referendum took place on 23rd June 2016. The UK electorate voted to leave the EU by a margin of 51.9% to 48.1% with a turnout of 72.2%. The result surprised many politicians and policy makers. The majority of major political parties had supported the campaign to remain in the EU, leaving great uncertainty about the potential outcomes of Brexit.

Any major political change at a national level can have serious implications on the broad range of energy, water, and food sectors. The UK energy system is connected to the EU in several ways that will be impacted by Brexit - from physical links through infrastructure (e.g. electricity and gas interconnectors), economic (favourable trade relations), managerial (companies such as EDF Energy working across borders), regulatory (shared legislation through Brussels and Strasburg, jurisdiction of the European Court of Justice) and population (workers from Europe, British citizens living in other EU states). Water policy, pricing and regulation in the UK is also controlled by the EU Water Framework Directive, while farm subsidies and environmental cross-compliance are predominantly driven by the EU Common Agricultural Policy. For energy, there has been an open European market since 2002. While Brexit will impact each of these sectors directly, the interactions among these sectors generate impacts that are not able to be foreseen if only a single system is considered.

2. Methods

2.1. Fuzzy cognitive mapping

Fuzzy cognitive mapping (FCM) is a simple approach used to extract mental models from people who possess various forms of knowledge about the causal interactions of a specific system. FCMs are a development of the cognitive maps used to elicit the causal structure of decision-making processes and social systems [24]. In a cognitive map, a number of characteristic features of the system (concepts) are identified and the causal connections (interactions) between these concepts are mapped using binary directional interactions in a signed digraph. Kosko [19] developed FCM primarily to address criticisms of the binary representation and the lack of dynamical analysis of system interactions in cognitive maps that are needed to predict changes in system components [25]. Kosko [26] later defined FCMs as 'fuzzy signed digraphs with feedback' where the interactions between components are weighted. FCMs have been used to map complex systems in diverse fields such as ecology, engineering, and medicine [27]. As well as being a useful approach to facilitate discussions between stakeholders, the semi-quantitative analysis of system dynamics provides an opportunity to conduct analyses of future scenarios.

2.1.1. Terminology

FCMs are a form of graph and as such a wide range of terminology applied in graph theory is often used when applying them. For the purposes of this study, we will refer to concepts (sometimes also termed nodes, vertices, components, or factors) which are connected by interactions (also termed edges, arcs or links). Concepts represent characteristic features of the system and are connected by a network of interactions. As signed digraphs, interactions in FCMs have a direction and a weight, reflecting the nature of the relationship between two concepts. Positive (or negative) interactions indicate that an increase in concept i will result in an increase (or decrease) in concept j. The weighting of the interaction reflects the strength of the impact. Weights are generally assigned a value $[-1, +1]$ depending upon the perceived strength of the interaction, where -1 indicates a strong negative relationship and $+1$ indicates a strong positive relationship. Weights are often assigned qualitatively by participants (e.g. “strong positive”, “medium positive”, “weak positive”) and later converted into numerical values [28]. The models created by expert participants are represented by an $n \times n$ adjacency matrix where W_{ji} is the strength (weight) of the interaction between concept j (the influencer) and concept i (the influenced) and n is the number of concepts. The final FCM is a representation of the understanding, expertise and opinion of the participants in the mapping process explained below [20,29].

2.1.2. Mathematical model of the FCM

Following the application of a mathematical function and assuming the model reaches a stable state, the value of each concept (C) can be interpreted in relative terms [20,28,30]. Each concept is assigned a value in an iterative process whereby a new concept value is calculated using the previous value of the concept plus the sum of all incoming concept values multiplied by their connection weights (Eq. (1)) (e.g. [30]):

$$A_i^{k+1} = f\left(A_i^k + \sum_{j=1,j\neq i}^{n} A_j^k W_{ji}\right) \tag{1}$$

where A_i^k is the value of concept C_i at iteration step k, W_{ji} is the weight of the interaction between C_i and C_j and f is the thresholding function. The process is iterative in that a change in state of one concept can impact a change in state of all concepts with which it has a causal relationship such that the value of a concept may change in multiple iterations [28]. Although linear approaches will result in a stable state in some instances, generally a thresholding or activation function (f) (e.g. sigmoid, logistic, or step function) is applied at each iteration in order to normalise concept values between 0 and 1. In this study we used a sigmoid function (Eq. (2)) where x is the value of a concept from Eq. (1).

$$f(x) = 1/(1 + e^{-x}) \tag{2}$$

2.2. Developing the FCM

Two workshops were held in November and December 2015 at the University of Leeds and the University of Cambridge to gather relevant expert participants and develop the FCMs. Workshops were advertised via an open invitation email sent to a UK Nexus Network mailing list, and targeted emails to identified participants. The mailing list (in May 2015) included roughly 30 European academics, 440 UK academics, 90 UK business contacts, and 35 addresses in UK governmental agencies.

In the first workshop, we created a systems model of the EWF nexus and its complex interactions by connecting separate FCMs for each of the EWF sectors through a fourth ‘nexus’ FCM. Each of the EWF FCMs were developed by participants with expert knowledge of that sector, and the ‘nexus’ FCM was developed by all participants working together. During this latter step, the participants identified interactions between existing EWF components, and added or aggregated concepts and their connections to create the ‘nexus’ FCM. Although aggregating FCMs about the same system has been suggested since Kosko [26], as far as we are aware this is the first time our approach has been used to develop and connect different systems to create a model of the interactions within and amongst those systems. The second workshop was designed as an independent review and assessment of each of the four maps (see 4 below) by a second group of experts (e.g. [20]).

At the start of the workshops, an explanation was given to participants about FCMs and their use. An unrelated example of how to construct an FCM was given, along with an explanation of how concept interactions were to be signed and weighted.

The FCMs were developed in a four stages:

1. Identification of concepts. The concepts perceived to be key to modelling UK demand for either energy, water, or food were identified by EWF subgroups. Each group was given a set of five ‘starter’ concepts [28], which need not be used in the mapping process, but were provided as examples of relevant concepts to help the subgroups begin their discussions.
2. Identification of interactions between concepts. Interactions were recorded as arrows from one concept to another (to signify direction) and were classified by the participants as either positive or negative (to signify the effect of the influencer on the influenced). Each interaction was also assigned a weight (weak, medium or strong) to represent the perceived strength of the interaction. Written guidance about how to determine the sign (effect) and weight (strength) of interacting concepts was provided to each group in the form of diagrams, for reference during the mapping process, with a goal of achieving a similar standard within and between groups. The nature of each interaction was determined deliberately by reaching consensus within the subgroup members.
3. Combining the individual FCMs. The three individual disciplinary-specific FCM maps for energy, water and food were combined by developing a “nexus map” that included connecting concepts from each EWF map. The “nexus map” was developed by all the participants working together at the end of the first workshop. Some concepts were identified to overlap (merge) whereas some concepts were linked with positive or negative causal relationships of varying strength by following the process outlined in step 2 above.
4. Review and assessment. During the second workshop, with all but two participants new to the FCMs, the EWF and nexus maps were reviewed and validated. Participants could add or remove concepts or interactions, or change the direction or weight of interactions.

Following the first workshop (in Leeds), and prior to the review and assessment of the model in the second workshop (in Cambridge), the paper FCMs were coded using the Mental Modeller FCM software package (http://www.mentalmodeler.org/), and printed diagrams of the coded models were used for the second workshop as they were easier to interpret than the hand-written and annotated originals.

2.3. Participants

A total of 23 experts participated in the workshops, 14 in workshop 1 and 11 in workshop 2, representing 12 different organisations. The majority of participants (78%) were from academic institutions. The remainder of the participants represented business (13%) and non-governmental organisations (9%) (see Appendix A). Encouraging participation from non-academics was challenging. However, many of the academic attendees had significant experience of working with stakeholders outside of academia and were able to feed this into the mapping process. Although some FCM studies engage around 50 participants (e.g. [31]), the number of experts in our study was typical of many participatory FCM investigations: for example, the number of participants often ranges from c.8 to c.30 (e.g. [20,21,31]). Moreover, our aim was not to provide a definitive answer to the effect of Brexit on the EWF nexus, but to explore how we could use FCM to capture the structure and dynamics of the three EWF sectors and combine them by using a fourth ‘nexus FCM’. In addition, because of the flexibility of the mapping process, we could easily add new maps, from individuals or groups, to the existing FCM, and use the current model as the starting point for an EWF participatory process.

2.4. Development of the aggregated FCM

The three models for energy, water and food contained 15, 23 and 24 concepts respectively. In all instances, more concepts and interactions were added during the validation exercise in the second workshop than were removed. Following the workshops, the weight assigned to each interaction was converted from a linguistic scale to a numeric value using a similar approach to Penn et al. [20], whereby:

+0.7 If the link is strong and positive (+ + +)
+0.5 If the link is medium and positive (+ +)
+0.2 If the link is weak and positive (+)
0 If there is no interaction
−0.2 If the link is weak and negative (−)
−0.5 If the link is medium and negative (− −)
−0.7 If the link is strong and negative (− − −)

The validated maps for energy, water and food were coded into adjacency matrices, and aggregated using the connecting concepts and interactions identified by workshop participants resulting in a map containing 50 concepts and 132 interactions. In order to reduce the map to a size suitable for scenario development and discussion, the combined map was simplified by means of qualitative aggregation [21,32,33]. Related concepts were combined to reduce the number of concepts, whilst preserving all interactions. Where combined concepts shared interactions with the same concept, the weightings were averaged. For example, "water variability", "temperature variability" and the "frequency and severity of extreme climatic events" were combined into one concept of "climatic variability". In this way, the map was consolidated into 29 concepts and 95 interactions. While the resulting model represented the consensus opinion of a particular group of experts (see "Potential bias of the expert panel" section below), it did include disciplinary knowledge across the energy, water and food sectors, including outside of the academic sector.

2.5. FCM analysis

Our analysis was carried out using the consolidated 29 concept FCM. We calculated three indices to characterise the role of each concept in the FCM. The centrality of a concept indicates how connected it is to other concepts in the system. In our analysis we use the sum of the absolute interaction weights to calculate centrality (i.e. it is based not only on the number of interactions, but also the weight of these interactions) [19]. The in-degree and out-degree inform our understanding of whether a concept is mainly influenced by the system or is influencing it. Concepts with a high in-degree (connected to by a large number of highly weighted interactions) are most influenced by the system. Concepts with a high out-degree (connect to other concepts with a large number of highly weighted interactions) are influencers of the system. Concepts can also be divided into types. Those concepts with a zero in-degree are not influenced by other concepts in the system, and were been seen by workshop participants as representing forcing factors (or transmitter concepts), known as 'drivers'. Receiver concepts have a zero out-degree and are not perceived to influence other concepts in the system [33]. To visualise our maps, we used the igraph package [34].

2.6. Scenario development

Following the vote to leave the EU, there is a degree of uncertainty over the nature of any future relationship between the UK and EU. We use the FCM generated in the workshops to test four scenarios (Table 1) of the possible future relationships between the UK and the EU in order to assess the potential impacts of different levels of UK-EU integration on energy, food and water demand in the UK. Scenarios are regularly created and expressed in a range of ways and for different purposes. In the UK, these scenarios range from the Government's Foresight approach that relies on expert opinion to paint pictures (e.g. [35]), via participatory scenario-building processes [36], through to those that are structured around mathematical models, such as the UK Energy Research Centre's Energy 2050 model [37].

The scenarios that we developed were based on recent analysis by the Financial Times [38] and other commentators on how the Brexit process could unfold. The first two scenarios relate to an 'Amicable Transition' and a 'Simple Separation', where the UK remains part of the EU single market on adjusted terms. The third scenario captures a 'Hostile Divorce' where the UK loses access to the EU single market and seeks to attract business by reducing regulation. The potential for weakened environmental regulation following Brexit has been highlighted by a recent House of Common's Select Committee report [39]. The fourth scenario captures a 'Clean Break', where the UK breaks ties completely but manages to agree on trade-terms. Before describing these scenarios in more detail, it is acknowledged that it is unlikely that any of them will capture the exact nature of the future UK-EU relationship. Rather, the idea is to capture the range of "exploratory scenarios" in terms of UK integration with EU and demonstrate how FCM can be used to explore the consequences for the EWF nexus.

The first scenario, **Amicable Transition**, is where the UK retains many of its links with EU, trading and supplying services through the single market. The UK remains largely bound by EU laws and regulations and makes contributions (or payments) at about 80% of those of full membership to the EU. As a result of continued free movement of people, the UK population is also expected to grow. The scenario represents soft Brexit with the development of a relationship similar to that of the Norwegians to the EU.

Simple Separation sees the UK retain access to the single market but in a less complete form than Scenario 1. Consequently, the obligations are lower with the financial cost about half of that of the previous scenario (ca. 40% of full membership). Services such as banking are no longer allowed free access and, as a consequence, GDP falls. This scenario is in accord with Irwin [40] where the "*UK retains a strong competitive edge in financial services, but most likely loses business as it becomes harder to provide certain services to EU markets*". Limited free

Table 1
Scenarios outlining the possible future relationships between the UK and EU on a scale from the most integrated to the least integrated scenario.

Scenario name	Amicable Transition	Simple Separation	Hostile Divorce	Clean Break
Bound by EU law	Yes	No, but reflects EU rules	No, only when trading	No, only when trading
Access to single market	Yes, goods & services	Yes, goods only	No	Yes, goods only
Free movement of people	Yes	Partial	No	No
Devolution within UK of policies and laws	No	No	Yes	Yes
Contribution to EU budget	Partial (~80%)	Partial (~40%)	No	No
Implications on concepts of the Fuzzy Cognitive Model				
Net migration to the UK	No change	No change	Decrease	Decrease
UK population size	Increase	No change	Decrease	Decrease
Gross Domestic Product	No change	Decrease	Decrease	Increase
Regulation	No change	No change	Decrease	No change

movement of EU citizens holds the UK population at its current level. The scenario still contains strong links between the EU and UK, akin to the level recently negotiated in the Comprehensive Economic and Trade Agreement between the EU and Canada.

The next two scenarios are both much 'harder' forms of Brexit. Both would see the UK have very limited or no access to the single market, make no contribution to the EU budget and have no free movement of EU citizens. The third scenario of a **Hostile Divorce** would see the UK suffer an adverse economic shock generated by lost access to the single market and have it respond by reducing regulation (including environmental) to attract business from abroad. The separation from EU continues to grow over time with increasing consequences; "*Regulatory divergence grows over time increasing the cost of trade, impacting on volumes and the UK place in supply chains*" [40] and the growth of GDP stalls.

The fourth scenario of a **Clean Break** is where the UK breaks ties completely with the EU but manages to agree on trade-terms that would see partial access to the single market. This scenario reflects the aspirations of many Brexiteers with full isolation from the EU, controlled migration leading to a falling population, and a buoyant economy generated by partial access to the single market and strong UK political control and regulation. The importance of this scenario is not simply that it demonstrates a hard form of Brexit, but that the model can still be used to suggest outcomes even if it is constructed from an imperfect sample, i.e. from the perspectives of people who most probably wished to remain in the EU.

To link these storylines to the FCM, four key concepts were selected for the scenario analysis: "net migration to the UK", "UK population size", "Gross Domestic Product (GDP)" and "regulation" (incorporating political control) (Table 1). These were chosen as they were:

- Core issues: Related/central to the key debates played out in the media prior to the referendum notably immigration, economic issues, and sovereignty [41–43]. A poll conducted prior to the vote by Ipsos MORI indicated that the most important issues to EU voting were: immigration (33%), the economy (28%) and the ability of the UK to make its own laws (12%) [44].
- Model components: Reasonably central to the system (Table 2).
- Sensitive to change: Identified as concepts that might be impacted significantly by the nature of the future relationship between the UK and the EU.

The four concepts were set to decrease, increase or remain unchanged under the different scenarios (Table 1). For Amicable Transition, only population size increased, reflecting that this transition was very close to remaining in the EU. All other concepts were unchanged. For Simple Separation, each concept was unchanged except GDP, which was assumed to fall due to reduced access to the single market in terms of services. For Hostile Divorce, all four concepts were set to decrease, while, for Clean Break, immigration and population were set to decrease, GDP was set to increase, and regulation was unchanged.

2.7. Scenarios analysis

Scenario analysis was conducted using FCMapper (www.fcmappers.net) (e.g. [45]), which uses Eqs. (1) and (2) to normalise the output values of concepts to between 0 ("low") and 1 ("high") [20,31].

In order to estimate the baseline scenario representing the steady state of the system where there has been no intervention or change, the initial value of each concept was set to 1 and Equation (1) iterated until the system reached a stable state (i.e. no change in concept values between subsequent iterations). Scenario analysis was conducted by fixing the initial value of one or more key concepts for each of the model iterations. This process is often called 'clamping' [22]. The initial

Table 2
List of concepts in the 29-concept consolidated model alongside measures of their centrality. Concepts that had zero out-degree or zero in-degree were classified as receivers or drivers, respectively. Concept in (or out)-degree is the sum of the absolute interaction weights.

Concept	Conceptual centrality	Out- degree	In- degree	Original map[b]	Concept type
Energy demand	6.25	0.00	6.25	**Energy**	Receiver
Sustainability Awareness	6.00	3.90	2.10	Nexus	
Renewable sources	5.68	3.10	2.58	**Energy**	
Climatic variability	5.23	4.33	0.90	Nexus	
Gross domestic product (GDP)[a]	5.10	3.00	2.10	Nexus	
Energy price	5.05	3.15	1.90	**Energy**	
Regulation[a]	4.55	3.65	0.90	Nexus	
UK population size[a]	4.35	4.15	0.20	Nexus	
Water demand	3.70	0.00	3.70	Water	Receiver
Lifestyle quality	3.00	1.20	1.80	**Energy**	
Infrastructure investment	2.60	1.20	1.40	Water	
Vegetable protein demand	2.45	0.70	1.75	Food	
Percent older people	2.30	1.60	0.70	**Energy**	
New technology	2.20	1.30	0.90	**Energy**	
Meat demand	2.20	0.00	2.20	Food	Receiver
Food price	2.15	0.80	1.35	Food	
Thermal comfort	2.10	0.70	1.40	**Energy**	
Infrastructure quality	1.95	0.60	1.35	Water	
Disposable income	1.75	0.65	1.10	Nexus	
Food waste	1.40	0.80	0.60	Food	
Population diversity	1.30	0.20	1.10	Nexus	
Sectoral competition	1.10	0.20	0.90	Water	
Percent single family dwellings	1.10	0.90	0.20	Water	
Supply chain efficiency	1.05	0.35	0.70	Food	
Net migration into UK[a]	1.00	0.80	0.20	Nexus	
Water price	1.00	0.20	0.80	Water	
Global warming	0.90	0.90	0.00	Nexus	Driver
Water quality incidents	0.70	0.50	0.20	Water	
Privatization/competition	0.40	0.40	0.00	Water	Driver

[a] Key concepts used in constructing scenarios.
[b] Nexus refers to concepts from the workshop connections maps, or concepts originating from at least two FCMs (Energy, Water or Food) which were merged during the post-workshops model simplification process.

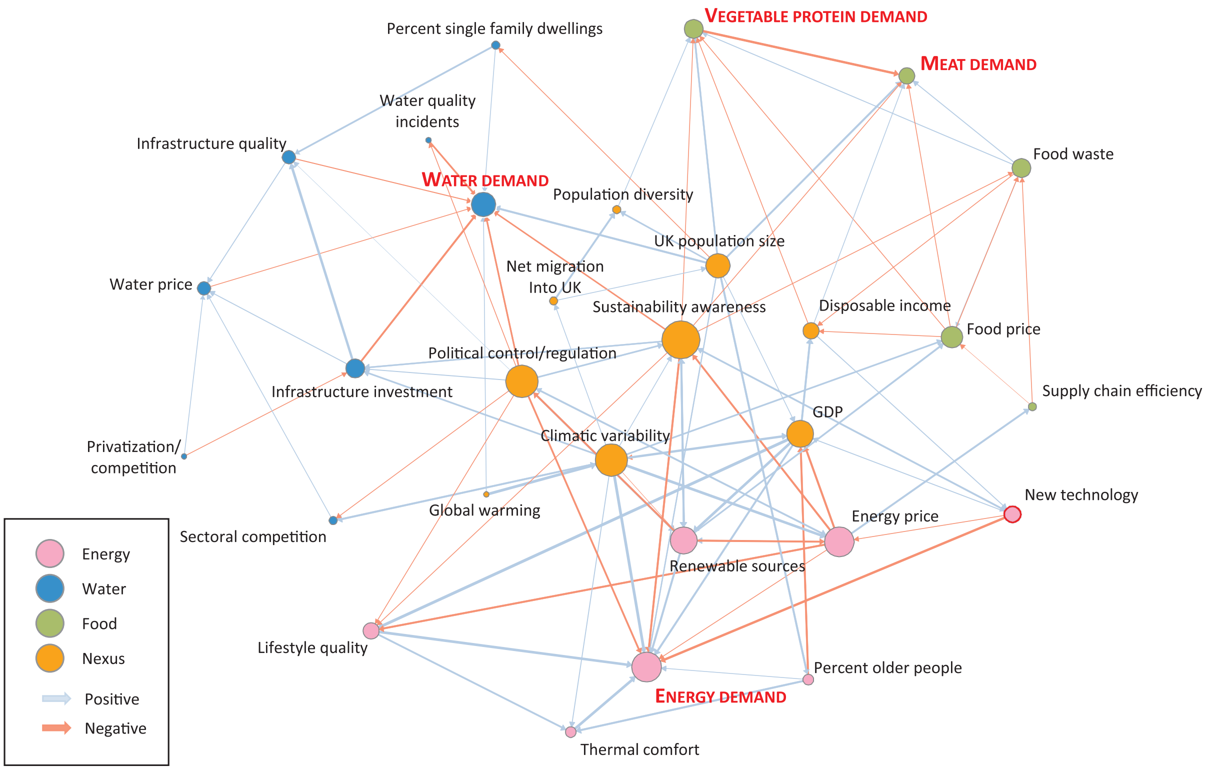

Fig. 1. Visual representation of the aggregated and reviewed fuzzy cognitive map developed during the participant workshops. 29 concepts are connected by 95 interactions. The direction of the arrow indicates the direction of the causal interaction between two concepts, the width of the arrow indicates the weighting assigned to this relationship, with thicker arrows having a stronger weighting (blue = positive, red = negative). The colour of each concept indicates its source map, where a concept was on more than one of the energy, water, or food maps, or was highlighted as a connecting concept by participants, it is identified as a 'nexus' concept. Demand concepts are highlighted with red labels in capitals. The size of the concept nodes is proportional to their centrality to the system. Larger nodes are more central concepts in the model.

valuescan be clamped high ("Increase" in Table 1), low ("Decrease"), or to their original values ("No change") determined during the mapping process [46]. Examining the relative change between the baseline steady state value for each concept and the value of each concept at the new steady state that results from the clamping procedure allows an assessment to be made of the impact of a change in the value of the clamped concept on the functioning of the system [33]. During the modelling procedure the system always reached a steady state in fewer than 20 iterations.

3. Results and discussion

3.1. FCM structure

The structure of the FCM and calculated indices are shown in Fig. 1 and Table 2. Energy demand was the most central concept, but it was a receiver concept (zero out-degree), meaning it had little influence on the system. Rather, energy demand had a high in-degree, indicating it was heavily influenced by changes in the values of other concepts. Awareness of sustainability and the proportion of energy from non-traditional sources were also central to the system. Both were 'normal' concepts, whereby they were both influenced by and influencers of the system. Excluding water demand, all of the top ten most central concepts were from either the energy or nexus (connecting factors) maps. There were nine 'nexus concepts' with centrality values ranging from 0.9 to 6.0. Five of these concepts were included in the top ten most central concepts, highlighting their importance in the structure of the FCM and their role in creating interdependence between the EWF maps.

The 29-concept model also contained two drivers: global warming and privatisation/competition. Global warming was the more central of the two drivers (Table 1). Three receiver concepts were identified by participants in this study: energy demand, water demand and meat demand (Table 1).

3.2. How does changing the values of key concepts affect demand for energy, water, and food?

In order to understand better how the EWF nexus could respond to change, we first examined the impact of changes to each key variable on the system in isolation, before considering the combined impact within the four scenarios. To compare scenarios, we observed the effect of a decrease in each of the key concepts (i.e. clamping to zero) on the EWF nexus. An increase would be expected to have the opposite effect. Fig. 2 shows the relative change in the values of other concepts when the value of GDP was artificially clamped to zero. The concepts most affected by a decrease in GDP are lifestyle quality and disposable income, which both show large relative decreases. Demand for energy, water and food are also impacted to some degree. As GDP is decreased there is less energy demand, a well reported relationship (e.g. [47]) with links through to disposable income and thermal comfort (a major consumer of energy) that feed into lifestyle quality. The reduction in energy demand itself drives a reduction in the proportion of new renewables and energy from non-traditional sources. As disposable income falls, there is an increase in vegetable-based protein demand and a corresponding decrease in meat demand and consumption [48]. There is only a slight decrease in water demand.

In contrast, a decrease in regulation causes a large relative increase in water demand (Fig. 3). This is partly due to an increase in water quality incidents, but also due to less investment in water infrastructure. Decreasing regulation has a small positive impact on GDP, which is in turn linked to an increase in lifestyle quality. Energy demand correspondingly increases, reflecting the scale of rise in GDP and the fall in energy prices. The slight increase expected in energy demand also illustrates the perception that political control constrains its use. Decreasing regulation has very little impact on food (protein) demand.

GDP and regulation have similar impacts on new technologies. The

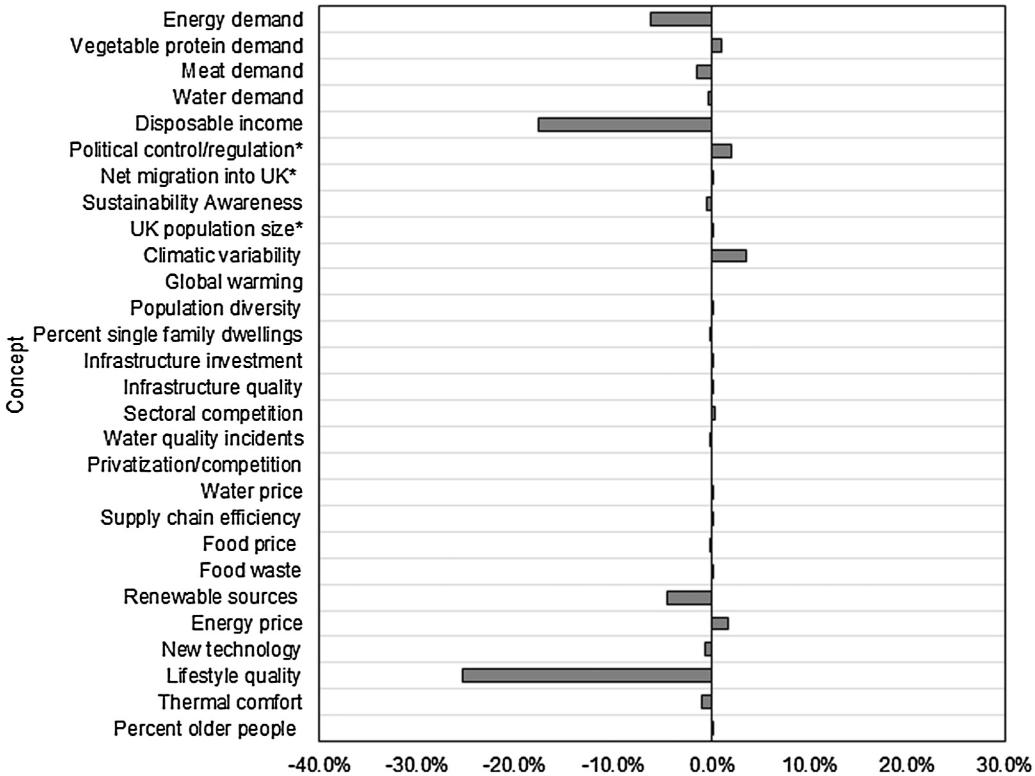

Fig. 2. The percent change on 29 model concepts for a decrease in GDP. Percent change is expressed relative to a baseline scenario where the Fuzzy Cognitive Model (Fig. 1) reaches a steady state in the absence of constraints.

perception amongst the experts indicates that a stronger economy and more control and regulation will increase the drive towards novel sources and uses of energy.

The impact of a decrease in net migration to the UK on all concepts in the system is explored in Fig. 4. There is a large relative decrease in population diversity (i.e. percent of non-British in the UK) and a decrease in the size of the UK population. The decrease in the size of the UK population leads to a decrease in demand for protein (both meat and vegetable based). Whilst energy demand changes very little, there is a decrease in water demand, perhaps a reflection of the reduced UK population size.

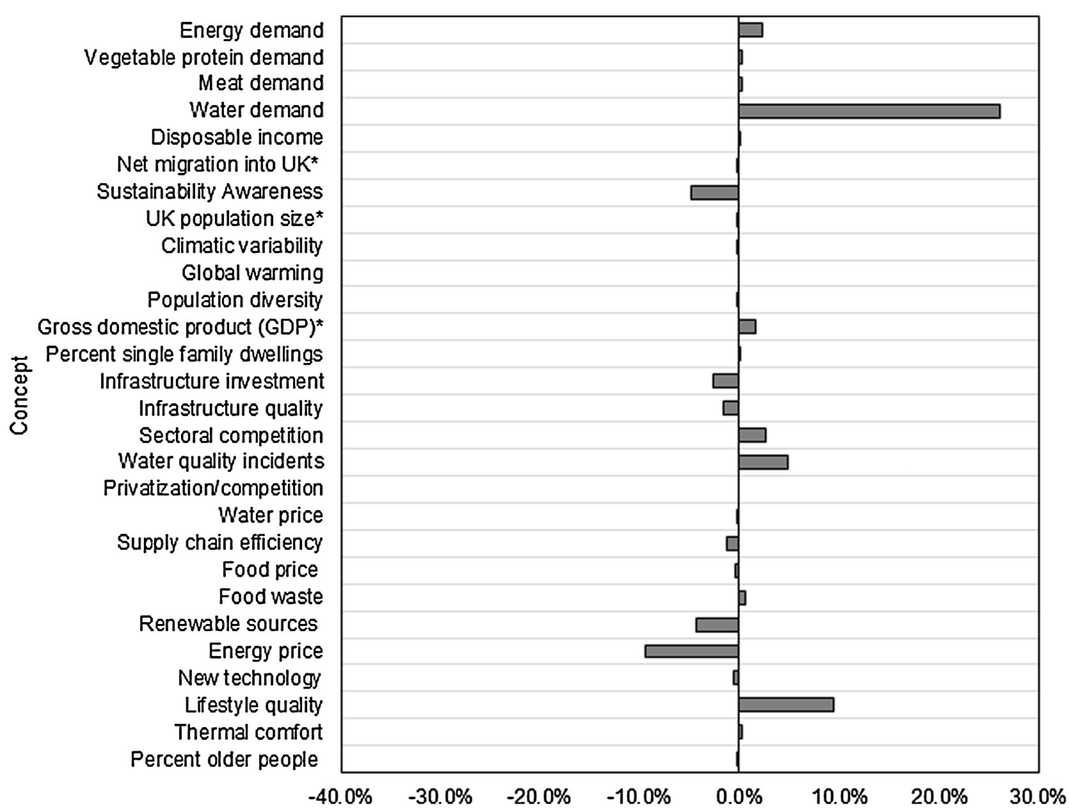

Fig. 3. Percent change on 29 model concepts for a decrease in political control and regulation.

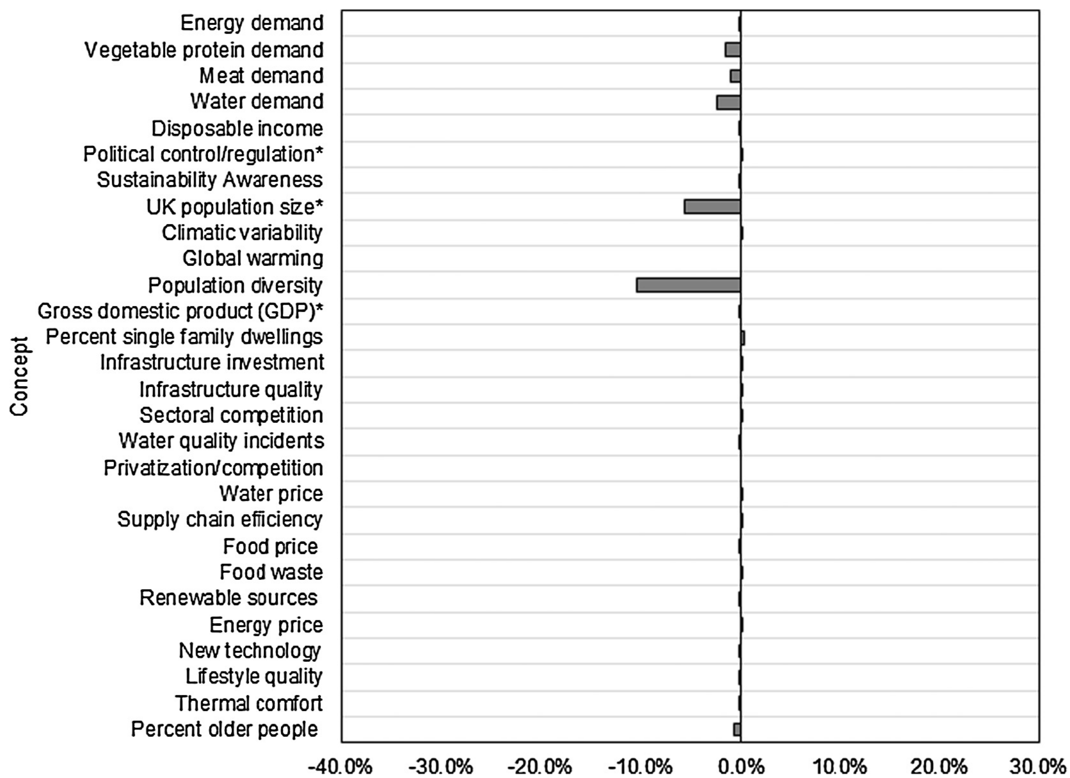

Fig. 4. Percent change on 29 model concepts for a decrease in net migration to the UK.

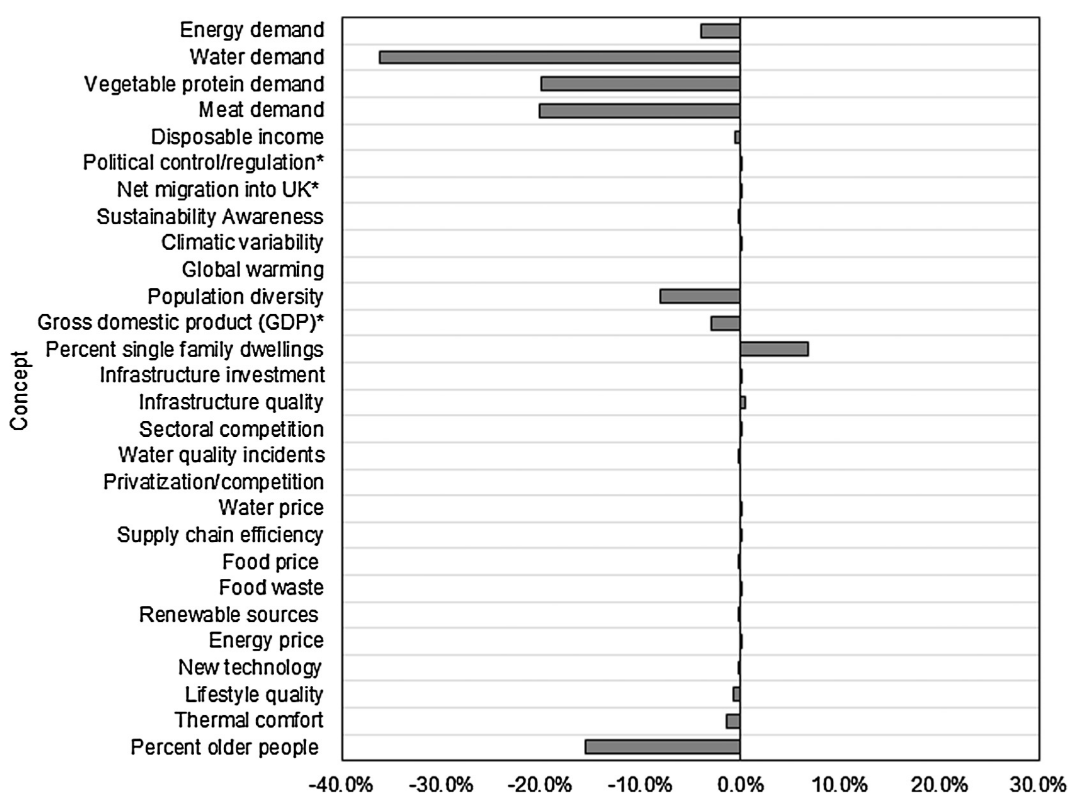

Fig. 5. Percent change on 29 model concepts for a decrease in the UK population size.

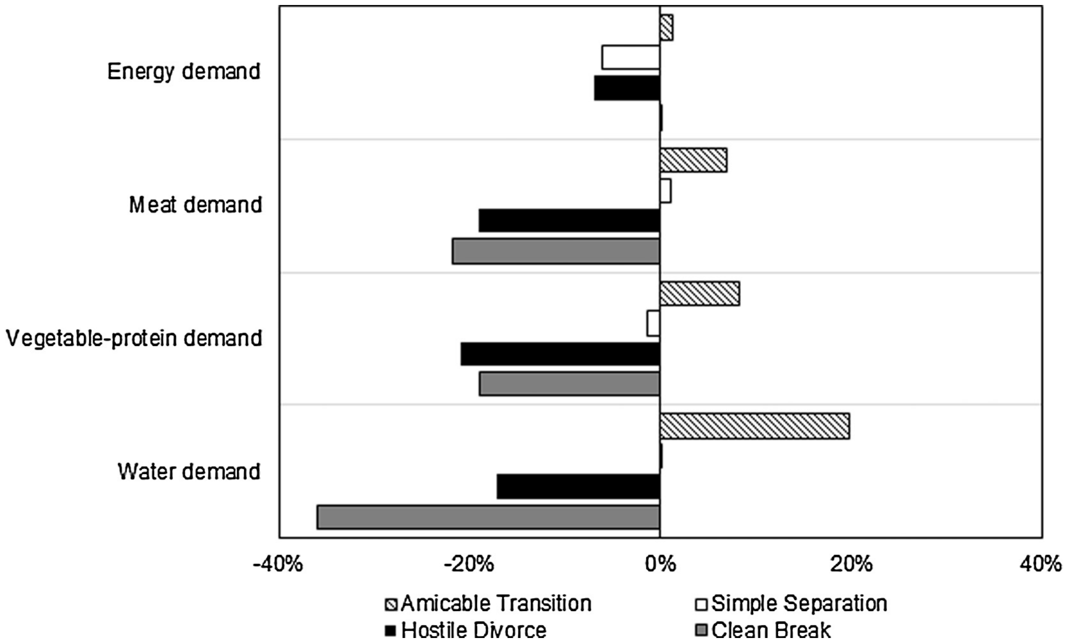

Fig. 6. Relative change for energy, water and food demand under different Brexit scenarios.

As intuitively expected, UK population size exerts a strong control on demand for energy, water and food - a decrease in population size will decrease demand for all three of these elements (Fig. 5). Of the four key concepts (GDP, regulation, UK population size, net migration to the UK), energy demand is most affected by a change in GDP, whilst water and food demand are more affected by changes in the size of the UK population.

3.3. Impact of different Brexit scenarios on the Energy-Water-Food nexus

The change in energy, water and food demand in the UK post-Brexit depends greatly on the future relationship between the UK and the EU. Fig. 6 shows the difference between the demand concept values for the four scenarios. A general trend is that total demand across the energy-water-food nexus will be reduced from the **Amicable Transition** scenario (which shows an increased demand) to a more disintegrated or 'hard' form of Brexit. These changes are largely influenced by decreases in the UK population size, and so do not necessarily reflect per-capita demand. However, energy is a notable exception and shows the smallest range of responses from among the four demand concepts (Fig. 6). Energy demand ranges from an increase of 1.2% under an **Amicable Transition**, declining by up to 7% under **Simple Separation** and **Hostile Divorce**, and is unchanged under the **Clean Break** scenario (Appendix B). The responses reflect the perceived relationship between energy demand and GDP. Any scenario showing a decline in the economy (smaller GDP) is likely to have lower total demand for energy, though per-capita demand should increase with a **Clean Break** given assumed declines in UK population size. Scenarios that would see a change in UK population size had the most impact on demand for food and water.

If the UK and EU remain fairly integrated, there is likely to be less change according to our participants. For example, 16 of 25 concepts were predicted to remain unchanged ($< 0.05\%$) under an **Amicable Transition** as opposed to only 3 of 25 under a **Hostile Divorce** (Appendix B). Less-integrated scenarios also resulted in the possibility for greater change. The average absolute change in **Hostile Divorce** and **Clean Break** was 4.23 times larger per concept than the change in the more integrated scenarios - with average absolute changes (excluding demand concepts) of 0.6%, 2.7%, 5.8% and 3.7% for the four scenarios, respectively. These two scenarios will see a decrease in older population and population diversity linked to overall depopulation trend. Lifestyle quality and disposable income, on the other hand, are massively degraded in **Simple Separation** and **Hostile Divorce** but increase with a **Clean Break**, presumably driven by GDP increases. The model also predicts an 11% reduction in renewable energy in the **Hostile Divorce** scenario.

4. New models needed for analysing the energy-water-food nexus

Different mathematical and statistical approaches have been used to model complex systems. Most approaches seek to mimic the detailed physical characteristics of systems and (sometimes) the inter-relationships among their individual components [15–18]. These approaches commonly undertake a comprehensive assessment of systems along the lines of Life Cycle Analysis (e.g. [15]), creating large and complex models that are capable of forecasting futures with apparent confidence due to the breadth of data they integrate from different disciplines. Many are known as integrated assessment models (IAM) or simply integrated modelling (IM). An example of IAM is used by the Inter-governmental Panel on Climate Change (IPCC) in their Assessment Reports, where they attempt to incorporate key human and natural processes required for climate change policy analysis by including activities that give rise to emissions, the dynamics of emissions and the responses (climatic, economic and environmental) [49]. These models are, however, often difficult to understand and interpret (e.g. [50]). In comparison, FCM takes a different and simpler approach to developing a transparent semi-quantitative model [12]. In our case, although the outputs of the FCMs are valuable, they need to be viewed in the relevant context. The final FCM reflects the mental models of a specific group of stakeholders at a specific point in time and it describes how those individuals believe the elements of a complex system interact and how it responds to future change. As such, the model outputs should not be viewed as objective forecasts of the future. The reliability of such FCMs can be increased in the future with additional models of each of the EWF sectors (e.g. [18,51]).

Although other systems-based approaches are used to model complex systems such as agent (or individual) based models, systems dynamics, and network models (e.g. [50,52,53]), we believe that FCMs are an alternative that are quicker (and likely cheaper) to develop; easily accessible to, and understood by, a wide range of stakeholder groups; valuable as a structured process for stakeholder engagement and discussion; readily adapted to incorporate new knowledge; and are able to capture the diversity of perspectives and opinions that drive policy decision making. Such decisions are not made on facts alone but also on people's mental models of the environment, economy, and society, how they interact, and how they think they will respond to change.

5. Potential bias of the expert panel

Our workshops were focused was on obtaining expert opinion about the interconnections of the EWF and effects of Brexit. However it is unlikely that the workshop participants reflect the voting population given their demographic characteristics. For example, a survey by the Guardian newspaper [54] showed that those with lower income and education levels voted to leave the EU, suggesting that the workshop participants (listed in Appendix A) would have been more likely to vote remain. This bias should not invalidate the results, but suggests that the model we constructed better represents the views of those who wanted to remain.

At the time of the workshops (November/December 2015), the opinion polls suggested that despite being close the ‘remain’ group were generally in the lead (e.g. see Financial Times Brexit Poll Tracker [55]). There could have been some complacency within the expert panel leading to a lack of engagement with the Brexit process. However, the situation could have strengthened our ability to collect their unbiased views as they were considering the situation without the passionate distortions that may have modified their responses. For example, if the same approach was carried out with those who voted leave the EU, a different model may have been constructed that would reflect the perceived advantages of Brexit; but neither model would be the ‘truth’ (which is the case for all participatory FCMs). However, there is still great value in the results that we produced as they represent the views and knowledge of experts in the fields of energy, water and food. By linking together three separate, expert-based, sectoral FCMs using a ‘nexus’ FCM, our new implementation of FCM development shows the potential for bringing together knowledge about the dynamics of different, but interconnected systems, to inform policy-making decisions about the nexus. This approach could be especially useful in situations such as Brexit where there may not be enough time to develop more complex systems-based models, and where a wide range of knowledge is needed. At the time of writing of this paper, after the referendum result in June 2016 but before the UK exiting the EU, a lot of different policies have been discussed. Outputs from a FCM such as the one developed here would be clearly valuable to inform such efforts.

6. The importance of Brexit to the energy sector

The energy sector in the UK is complex, covering a breadth of processes (energy capture, conversion, storage, distribution, use and efficiencies) and infrastructure (including power stations, fuel storage systems, cable grids and pipelines and equipment that uses it). The complexity is increased by interactions both with other sectors (e.g. food and water) and with other countries (both inside and outside the EU). At the time of writing, negotiations determining the UK’s withdrawal from the EU have only just started and could take very different directions. One thing that is clear is the potential impact on the energy sector.

The consequences will vary for the different sections of the energy sector as we generate, trade and use energy from multiple sources. A commonly recognised shift will be through regulation, which is likely to move back to independent UK law, rather than interpretations of EU legislation through UK laws. There are further complications with accompanying agreements with European partners. For example, the European Atomic Energy Community (Euratom) was established alongside the EU in 1957 to support the nuclear industry by creating a functional business environment through regulation and financial support. The confidence from Euratom empowers the market in nuclear power between its members and dictates how they interact with non-EU states.

The triggering of Article 50 for Brexit does not guarantee that UK will leave Euratom; a rapid departure could be catastrophic for the UK nuclear industry [56]. However, the Euratom Treaty is linked to the EU Treaty and are both managed by the European Court of Justice (ECJ), so negotiation will have to take place. The style of Brexit may determine the rate and level of implementation of change; if, as some politicians interpret, Brexit means all legislation is UK defined then the link to ECJ will force resignation [57]. As of now it is impossible to know how much is posturing and the direction and extent of change.

The FCM approach described here, could prove informative for specific questions such as Euratom. It does not attempt to model the truth, but people’s perception of the functioning of complex systems. The information obtained is often as valuable in improving the understanding of why parties hold specific views and indicates their strength of feeling.

7. Conclusion

We developed and applied a FCM approach to analyse the consequences of Brexit for UK energy, water and food demand. Prior to the Brexit referendum, 23 experts co-developed a fuzzy cognitive map during two participatory workshops. The map highlights the key interactions involved in energy, water and food demand in the UK. In order to examine future UK-EU relations following Brexit, we also tested how four key concepts influenced features of the EWF nexus. Of the four key concepts identified as likely to change, energy demand was most affected by a change in GDP, whilst water and food demand were more affected by changes in the size of the UK population. When used to examine different Brexit scenarios, the FCM projects greater changes in the demand for energy, water, and food as the UK becomes less integrated with the EU. More broadly, our results show how fuzzy cognitive mapping can help to capture the diversity of expert perspectives about a complex change in policy and legislative structure that will affect energy usage, and be used to identify key concepts and interactions that could be important for policy decisions.

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Appendix A. Workshop participants

List of participants in the two workshops in which the Fuzzy Cognitive Model was developed (WS1 - Leeds, November 2015) and validated (WS2 - Cambridge, December 2015).

Organisation	Job Title	Sector	Gender	WS1	WS2
University of Manchester	PhD Student	Academia	Male	Y	
NERC Centre for Ecology & Hydrology (CEH)	Researcher	NGO*	Male	Y	
University of Manchester	Postdoctoral Research Assistant	Academia	Male	Y	
University of Leeds	Professor Emeritus	Academia	Male	Y	
University of Leeds	Associate Professor	Academia	Female	Y	
University of West England	Professor	Academia	Male	Y	
University of Leeds	Lecturer	Academia	Male	Y	Y
University of Manchester	Lecturer	Academia	Male	Y	Y
University of Manchester	Project Manager Oil & Energy	Academia	Male	Y	
University of Leeds	PhD Student	Academia	Male	Y	
University of Leeds	PhD Student	Academia	Male	Y	
Anglia Ruskin University	Lecturer	Academia	Male	Y	
University of Leeds	Professor	Academia	Male	Y	
University of Leeds	Professor	Academia	Male	Y	
MWH Global	Design Engineer	Business	Male		Y
Cranfield University	Professor	Academia	Female		Y
Mott MacDonald	Sustainability Strategist	Business	Male		Y
Cambridge University	Lecturer	Academia	Male		Y
Anglia Ruskin University	Visiting Fellow	Academia	Male		Y
The Flow Partnership	Global Network Developer	NGO*	Male		Y
University of Exeter	Lecturer	Academia	Male		Y
Mott MacDonald	Principal Hydrogeologist	Business	Female		Y
City University London	Teaching Fellow	Academia	Female		Y

*NGO = Non-governmental organisation.

Appendix B. Appendix B

Percent change in all unconstrained concepts for the four scenarios detailed in Table 1.

	Concept	Amicable Transition (%)	Simple Separation (%)	Hostile Divorce (%)	Clean Break (%)
Energy	Percent older people	5.1	0.0	−15.6	−15.6
	Thermal comfort	0.4	−1.0	−2.1	−0.7
	Lifestyle quality	0.0	−25.2	−16.3	16.5
	New technology	0.0	−0.6	−1.2	0.3
	Energy price	0.0	1.5	−7.2	−0.9
	Renewable sources	0.0	−4.5	−11.0	2.2
Food	Food waste	0.0	0.1	0.8	0.0
	Food price	0.0	−0.1	−0.7	0.0
	Supply chain efficiency	0.0	0.2	−0.9	−0.1
Water	Water price	0.0	0.0	0.0	0.0
	Privatization/competition	0.0	0.0	0.0	0.0
	Water quality incidents	0.0	0.0	4.7	0.0
	Sectoral competition	0.0	0.5	3.2	−0.4
	Infrastructure quality	−0.2	0.0	−0.9	0.5
	Infrastructure investment	0.0	0.2	−2.3	−0.2
	Percent single family dwellings	−3.1	0.0	6.8	6.8
Nexus	Population diversity	2.8	0.0	−20.8	−20.8
	Global warming	0.0	0.0	0.0	0.0
	Climatic variability	0.0	3.5	3.5	−2.6
	Sustainability Awareness	0.0	−0.5	−5.9	0.2
	Disposable income	0.0	−17.6	−17.6	9.8
Demand	Water demand	19.7	0.1	−17.2	−36.1
	Meat demand	8.3	−1.4	−21.0	−18.9
	Vegetable protein demand	6.9	1.1	−19.1	−21.8
	Energy demand	1.2	−6.2	−7.0	0.0

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