Environmental Science Advances

PAPER

View Article Online
View Journal | View Issue

Cite this: *Environ. Sci.: Adv.*, 2022, **1**, 305

Interrelationship study of the impacts of hydraulic fracturing on the environment and socioeconomic activities: a novel approach to finding sustainable solutions†

Aniekan E. Essien, *[a] Katie White[a] and Mariam Mohammadi[b]

Global energy governance is highly influenced by the increasing energy demand, dwindling conventional energy systems, and socioeconomic activities. The continuous energy demand resulting from the increase in urbanization and industrialization leads to aggressive exploitations of alternative energy sources and unconventional hydrocarbon systems. Consequently, hydraulic fracturing is given greater consideration despite its potential impacts on the environment and socioeconomic activities. For the first time, the interaction and feedback loops between the exploitation of shale gas using hydraulic fracturing and the three pillars of sustainability (environmental, social, and economic) are extensively studied. Using the Fylde community at Lancashire in the UK as the research study area, this paper aims to assess the impacts of hydraulic fracturing on the environment and socioeconomic activities to find the best and most sustainable solutions to shale gas exploration and exploitation. Decision Making Trial and Evaluation Laboratory (DEMATEL) method was used to indicate the relative importance and influence between the key sustainability themes (elements). To design a robust and result-oriented program for the shale gas exploitation using hydraulic fracturing, the key sustainability themes with the greatest influence were used. These included local economic activity, energy security, employment rate, and water quality. The derived best and sustainable solutions for shale gas exploitation using hydraulic fracturing for the Fylde community drawn from the DEMATEL model simulation and the stakeholder analysis included enhanced hydraulic fracturing technology, provision of funding by the government, publication of environmental studies reports, implementation of key policies, and community engagement.

Received 3rd February 2022
Accepted 20th May 2022

DOI: 10.1039/d2va00023g

rsc.li/esadvances

Environmental significance

The call for the complete decarbonization of the global economy has increased, and therefore, it is imperative to find sustainable solutions to exploiting more natural gas as a transition fuel. Although shale gas is considered to have a relatively low carbon footprint as a fossil fuel source, it is highly contentious due to factors such as environmental pollution and induced seismicity. This paper presents the state-of-the-act interactions and feedback loops between shale gas exploitation using hydraulic fracturing and the key elements of sustainability, which are depicted in the coupled system diagram. This was achieved using the DEMATEL simulation. The best and most sustainable solutions derived for shale gas exploitation for the Fylde community drawn from the DEMATEL model simulation and the stakeholder analysis summarized the robust sustainable solutions to hydraulic fracturing activities, which could be used as a model for other regions and other environmentally impacting related projects such as landfill construction and power station installation projects.

1 Introduction

The continuous exploration and, in most cases, exploitation of the earth for energy sources, either sustainable or not, has proven that sufficient, cheap, and efficient energy is the life-blood of industrialization and modern civilization.[1–3] This is evident in the feedback reported between industrialization and economic development which have cemented humans' unending need for energy, therefore, culminating in a positive relationship between socioeconomic development and industrialization.[4,5] Nevertheless, in all these interrelationships and feedbacks, water resources and the environment at large, tend to be most negatively impacted.[6,7] Water is life,[8] therefore, one could say it is the greatest resource that deserves protection from degradation caused by anthropogenic activities, such as energy extraction.

Growth in energy demand always increases the potential of countries seeking unconventional ways of hydrocarbon

[a]Department of Civil Engineering, McMaster University, Hamilton, Ontario, Canada, L8S 4L7. E-mail: essiena@mcmaster.ca

[b]HLV2K Engineering Limited, Ontario, Cananda, L5L 1X2

† Electronic supplementary information (ESI) available. See https://doi.org/10.1039/d2va00023g

extraction.[9] The UK is of no exemption even following its set target to bring all greenhouse gas emissions to be net zero by 2050.[10] While natural gas seems to be a good fit for a transition energy source to a net-zero economy in the UK, it is imperative to note that the continuous importation of liquified natural gas (LNG) from other countries to offset the energy demand may not be environmentally and economically friendly. This is due to the high energy requirements for LNG's liquification, transportation, and regasification before reaching the consumers.[11] Moreover, if LNG importation by the UK increases, domestic shale gas production seems more beneficial to reduce or maintain low greenhouse gas emissions. In addition, hydrogen gas (H_2), a zero-carbon fuel, can be produced *via* steam methane reformation (SMR) with carbon capture using shale gas, which is relatively cheap.[11]

Hydraulic fracturing is one of the methods of sourcing unconventional fossil fuel; it can simply be defined as an exploitation of an unconventional hydrocarbon system.[12] The extraction of shale gas through hydraulic fracturing may be considered the key player amongst all the unconventional energy resources exploitation following depleting conventional hydrocarbon systems, and for many years, several countries are continuing to explore this option. For example, in the past 20 years, just before the UK government introduced the moratorium on hydraulic fracturing in 2019, the dwindling oil reserves in the North Sea and low oil price prompted the UK to consider hydraulic fracturing of the Lancashire shale gas field with the hope of maintaining the UK gas supply security and potential exportation to trigger the much-needed economic stimulus.[13] And while some states and provinces in the US and Canada, respectively, share different opinions on its costs and benefits following the rapid growth of shale gas production through hydraulic fracturing, other countries, such as Russia and China, are investing and developing unconventional hydrocarbon fields, which may include the Arctic.[14,15]

Consequently, the exploration and exploitation of unconventional hydrocarbon resources through hydraulic fracturing could be said to be highly contentious anywhere in the world, the UK included. Many of the arguments are usually triggered by the poor approaches used by the key stakeholders (*i.e.*, oil companies and governments) during the exploration and exploitation activities. The UK's richest shale gas formation is the Bowland Shale gas formation.[16] Considering that the Bowland basin, where the Fylde community is seated, is the most economically viable shale gas formation in the UK,[16] the Fylde district council at Lancashire in the UK was used as the research study area without emphasis on the potential environmental and socioeconomic impacts from its past hydraulic fracturing exploration activities. This paper aims to assess and evaluate the costs and benefits, interactions, and feedback loops between the social, economic, and environmental systems associated with shale gas exploration and exploitation activities. In addition, the paper aims to provide the best and most sustainable solutions to hydraulic fracturing activities with the objective of maintaining the quantity and quality of water resources and enhancing socioeconomic development.

2 Methodology

2.1 Research context – study geographical boundary

To contextualize the study, a local government (Fylde district council) in the UK was selected as the research study area. The research was constructed based on how shale gas exploitation activities could be designed without significantly impacting the environment and socioeconomic activities while benefiting all the stakeholders in the Fylde community. The key components of the study area used to derive the stakeholder analysis and for the simulation of the DEMATEL model were briefly discussed in the later section.

2.1.1 Social system. Fylde is an area of about 166 square kilometres with a population of 81 211 in 2020, and it is in the historic county of Lancashire, north-western of England (Fig. 1).[17] In 2019, it was recorded that 16% of the population of the community were under 16 years of age, 57% of the population were between the age of 17 and 64, and 27% of the population were over 65 years of age.[18] The increase in population in the Fylde community was viewed positively by the community due to their historically low fertility rates.[17] In 2019, the ministry of housing, communities and the local government stated in their report of the English indices of deprivation that Fylde has a moderately low total deprivation ranking. Moreover, in the previous year, 9.7% of families in Fylde were indicated to be in fuel poverty, and the three major indicators that simulate this are the cost of energy, the energy efficiency ranking of the housing property, and the family income.[17,19]

Fylde is predominantly a rural area with a smaller urban area. It is one of the top hot spots for tourism experience as it is enriched with pretty villages, wetlands, seaside, canals, and dune areas;[22] hence providing countryside adventures, such as horse riding, walking, cycling, and canoeing. Fylde is very rich in sporting culture, and it is known for its golfing tradition.[23]

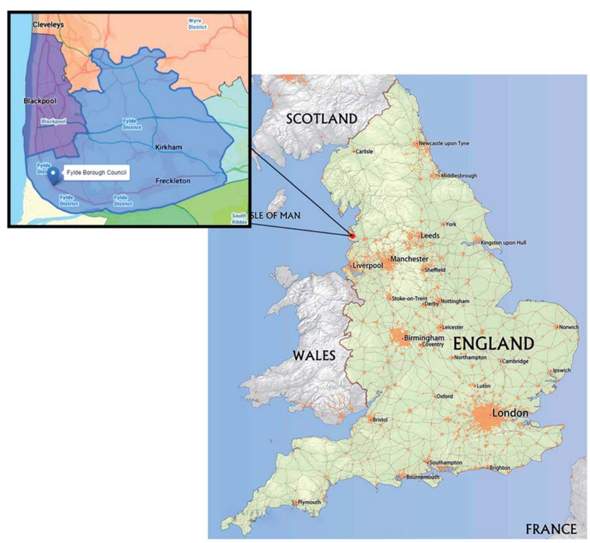

Fig. 1 Map of Fylde district council: the blue-shaded parts in the map indicate the area covered by Fylde.[20,21]

2.1.2 Economic system. Most of Fylde can be said to be a rural area, but it is home to organizations with international reputations. It has been reported that, even though Fylde is comprised predominantly of rural areas, it is not as deprived as some urban areas in England.[24] However, in comparison to most rural areas in England, the district has the lowest employment in the service sector and other industries, such as nursing, teaching, and oil and gas *etc.*, but one of the highest in the manufacturing sector. This is due to the presence of industries like the aerospace industry and chemical industry, such as BAE Systems and Westinghouse Springfields, respectively.[18] The Fylde district economy partially depends on tourism which is subjected to the biodiverse crude environment to entice tourists.[18] In the Fylde community, earnings per gender analyses indicate that males earn 19% more than women for full-time jobs.[25]

2.1.3 Environmental system. Over the years, Fylde has had little or no history of heavy industrialization, but there had been a minor legacy of industrial activities which may have made its environment prone to high-level potential pollutants due to unknown abandoned sites.[26] The district of Fylde is passed across by the M55 Motorway and has been recognized to provide direct access to the Motorway network.[17] Nevertheless, this may be one of the major contributors to potential air pollution and the ongoing microplastic pollution of the area's coast shores.[27]

In addition to the two major rivers in Fylde, River Ribble and River Wyre, Fylde is enriched with a beach called St. Anne's beach and seafront. River Wyre flows through Lancashire, and it has several biotopes of which some have been identified under international and national statutory environmental designations which include the Forest of Bowland Area of Outstanding National Beauty and the Morecambe Bay.[28] Fylde is a coastal plain between the Morecambe Bay to the north, the Ribble estuary to the south, the Bowland hills to the east, and the Irish sea to the west in the western Lancashire.[29] The Fylde aquifer and rivers are the major sources of water for United Utilities (previously known as North West Water), and sources of water for abstraction by many industries and private entities.[30] With regards to land use, the principal land use in Fylde is for agricultural activities due to its soil richness.[31]

2.2 Sustainability assessment

Following the systems approach, the authors defined the three pillars of sustainability as three distinct systems (environmental, social, and economic) in which their key elements interact.[32] In addition, the meaning of sustainability for an economist is different for an environmentalist and socialist; therefore, one could say sustainability is subjective.[33] With respect to this, the authors selected the key themes for environmental considering the key environmental receptors prone to the impact of hydraulic fracturing; for social, the chosen themes were aimed to mitigate the potential impacts of hydraulic fracturing on the health and well-being of individuals and the community (Fylde); the economic considered the impact of hydraulic fracturing to the local and nationwide economy.

A general literature review was conducted to understand the costs and benefits of hydraulic fracturing with respect to the three pillars of sustainability. More specifically, key elements within each pillar (environmental explored water quantity, water quality, land use, air quality, and wastewater; social explored physical health, mental health, resource availability, and well-being; economic explored employment rate, local economic activity, energy price, and energy security) were highlighted and explored to create the groundwork for the simulation of the DEMATEL model as well as determining the best and most sustainable solution for implementing hydraulic fracturing in the Fylde community. The output of this step is a comprehensive table outlining the costs and benefits of all key themes for each pillar of sustainability.

2.3 Stakeholder analysis

The Fylde district council was used to establish the stakeholder analysis through the process of identifying the potential stakeholders that may be involved and/or impacted by shale gas exploration and exploitation activities. The prioritization and understanding of the stakeholders were conducted by analysing their level of influence and level of interest as well as their needs and feelings. The stakeholders were scoped to include the community of Fylde and other key organizations that may be impacted by the hydraulic fracturing project. Once identified, each stakeholder group was critically evaluated, a rating on their level of interest and influence was determined. This rating is required to determine what level of involvement, at what stages, will benefit that stakeholder group. For example, a stakeholder group that is considered as low influence and low interest, is best to remain informed and consulted; whereas if they are considered high in both influence and interest, it is best to inform, consult, and collaborate with them.[34]

Once ratings are appointed to each stakeholder group, to ensure a successful project, it is important to understand their needs, feelings, and understanding of the project. This understanding will allow for a communication or engagement plan to be developed to understand what stakeholder group needs to be supportive to ensure the project is successful (*i.e.*, high influence and high interest), and which group is a benefit to be supportive, but is not a requirement (*i.e.*, low influence and low interest). While typically this assessment would be conducted utilizing interviews with stakeholder groups, for the purpose of this paper, the authors utilized previously conducted interviews found in existing literature.

2.4 Identifying potential solutions

This research was done initially as segregated potential solutions with the end goal of combining a series of case study-specific potential solutions to improve the problems that may arise due to implementing hydraulic fracturing in the Fylde community. This step attempted to be an exhaustive list of solutions to address "pain points" highlighted in the sustainability assessment.

2.5 Solution identification and coupled system: DEMATEL method

To determine the best and most sustainable solution for the Fylde community, the Decision Making Trial and Evaluation Laboratory (DEMATEL) method was utilized to first determine the relative importance and influence between key sustainability themes identified in the impact assessment. The DEMATEL method is known as a structural modelling approach, specializing in converting interdependency relationships into a cause-and-effect group *via* matrices and finding the critical factors in complex coupled systems.[35–38] DEMATEL comprises of four steps: the creation of a direct-influence matrix, the establishment of the normalized direct-influence matrix, construction of the total-influence matrix, and creation of the influential relation map (IRM) (for this paper, informing the coupled system diagram).[35]

The creation of the direct-influence matrix requires expert knowledge to determine the level of influence between two key themes (defined in the sustainability assessment), utilizing a pre-defined scale (0 – no influence, 1 – low influence, 2 – medium influence, 3 – high influence, 4 – very high influence). This step can be depicted by eqn (1)

$$Z = \begin{array}{c|cccccc} & \boldsymbol{t_1} & \boldsymbol{t_2} & \boldsymbol{t_3} & \cdots & \boldsymbol{t_j} \\ \hline \boldsymbol{t_1} & 0 & z_{t_1t_2} & z_{t_1t_3} & \cdots & z_{t_1t_j} \\ \boldsymbol{t_2} & z_{t_2t_1} & 0 & z_{t_2t_3} & \cdots & z_{t_2t_j} \\ \boldsymbol{t_3} & z_{t_3t_1} & z_{t_3t_2} & 0 & \cdots & z_{t_3t_j} \\ \vdots & \vdots & \vdots & \vdots & 0 & \vdots \\ \boldsymbol{t_i} & z_{t_it_1} & z_{t_it_2} & z_{t_it_3} & \cdots & 0 \end{array} \qquad i,j = 1,2,3,\ldots,n \tag{1}$$

where n is the number of key themes evaluated, $t_{i,j}$ is the key theme being evaluated, Z_{t_i,t_j} is the influence ($z_{t_i,t_j} = 0, 1, 2, 3, 4$) of the first key theme on the second key theme (*i.e.*, Z_{t_3,t_n} is the influence t_3 has on t_j) and the influence of any key theme on itself is zero (*i.e.*, if $i = j$, $z_{t_i,t_j} = 0$), and Z is the direct-influence matrix.[35–38]

The direct-influence matrix (Z) must then be normalized to create the normalized direct-influence matrix (X) which can be achieved by eqn (2) and (3).[35–38]

$$X = \frac{Z}{s} \tag{2}$$

$$s = \max\left(\max_{1 \le i \le n} \sum_{j=1}^{n} z_{t_it_j}, \max_{1 \le i \le n} \sum_{i=1}^{n} z_{t_it_j}\right) \tag{3}$$

In summary, eqn (2) and (3) depict dividing the entire direct-influence matrix (Z) by the maximum value of the exhaustive summation of each row or column to create the normalized direct influence matrix (X).

To construct the total-influence matrix (TM), the direct and indirect effects of the normalized direct-influence matrix (X) are summed using eqn (4)

$$\mathrm{TM} = X + X^2 + X^3 + \ldots + X^h = X(I - X)^{-1} \text{ when } h \to \infty \tag{4}$$

where I is an identity matrix.

Finally, to produce the IRM (to inform the coupled system diagram), the vectors R and C must first be determined by summing each individual row and column of the total-influence matrix, as depicted in eqn (5).[35–38]

$$R = \left[\sum_{j=1}^{n} tm_{ij}\right]_{nx1}, \quad C = \left[\sum_{i=1}^{n} tm_{ij}\right]_{1xn}^{T} \tag{5}$$

The importance level highlighting the strength of influence that are given and received, or the degree of central role for that key theme, can be determined by summing ($R + C$). Furthermore, the relationship of a key theme on the system can be determined by taking the difference of ($R - C$).[35–38] Where a positive ($R - C$) value represents a key theme that has a net influence on the system, which is defined as a "cause". Alternatively, a negative ($R - C$) value represents a key theme that is being influenced by other factors, which is defined as an "effect".[35–38] The importance and influence values can then be summarised into an IRM, which can provide valuable insight for decision decision-making.

To ensure the most valuable information is displayed in the resultant coupled system, a threshold value must be determined, whereby if the relationship within the total-influence matrix (T) is below the threshold, that influence arrow will not be drawn. The threshold value (α) is determined by averaging all values within the total-influence matrix (eqn (6)).[35–38] This process is then used to inform the coupled system diagram (including key theme importance and presence of uni-directional or bi-directional influence arrows), which then is combined with the identifying potential solutions stage to conclude in a series of informed solutions for Fylde to integrate hydraulic fracturing into their community.

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} tm_{ij}}{n^2} \tag{6}$$

3 Results and discussion

3.1 Sustainability assessment

This section, which is extensively discussed in S1 (ESI†), explores the implications of hydraulic fracturing on the environmental (water resources, land use, air quality, and wastewater), social (physical health, mental health, resource availability, and well-being), and economic (employment rate, local economic activity, energy security, and energy price) pillars of sustainability. A summary of the findings drawn from S1 (ESI†) and other existing literature can be found in Table 1.

3.2 Stakeholder assessment

3.2.1 Stakeholder identification. Shale gas exploration and exploitation projects could be said to be one of those projects

Table 1 Summary of the benefits and costs of shale gas exploration and exploitation activities on the key themes for each pillar of sustainability S1 (ESI).[39–61]

Sustainability pillar	Key theme	Benefits	Costs
Environmental	Water quantity	– Uses less water from mining to the generation of power in comparison to other energy source, such as coal and nuclear	- Increase in water use
	Water quality	- Shale gas exploited areas result in the provision of extensive baseline information on groundwater	- In the event of spillages and leakages, hydraulic fracturing could lead to groundwater and surface water pollution
	Land use	– An appropriate CO_2 emission could lead to enhancement in plant growth. According to the study by NASA, assuming the CO_2 recorded in 2000 doubled by the year 2080, some crops may increase their yield[62]	– Increase in land cover increases catchment imperviousness, potentially leading to flash flooding – An increase in erosion due to an increase in soil imperviousness could result in eutrophication – The use of explosives (dynamite) during seismic surveys could disturb biodiversity – Spillages from drilling wastes could cause land contamination – The potential destruction of landscape and stripping off its vegetation
	Air pollution	- Gas produced from hydraulic fracturing is generally cleaner than gas from coal and petroleum extraction - Greenhouse emission from shale gas use possesses relatively shorter life cycle - Reduce carbon footprint due to minimizing gas liquidation and transportation - Reduction of acid rain as natural gas is chemically inert when incinerated	– Dust generation could lead to air quality disturbance, which could result to an increase in heat absorption, leading to an increase global warming – Some of the shale gas components and derived chemicals are mutagenic and carcinogenic, such as mercury and benzene – Increase in global warming in event of methane gas leakage into the atmosphere
	Wastewater	– If properly treated and disposed of effectively, it could balance and/or increase water availability	– Reinjection of wastewater to the sub-surface is known to be the major cause of minor earthquakes associated with hydraulic fracturing – Spillages of flowback and produced water (FP) which is known to be rich in brine, toxic metals, and radioactive materials could lead to land contamination
Social	Physical health	N/A	- Risk of physical health implications based on the distance to hydraulic fracturing site: o high (0–1 km), o Moderate (1–3 km), and o Low (>3 km)
	Mental health	- If hydraulic fracturing is perceived to be positive, an individual may become hopeful, eager, or pleased	- If hydraulic fracturing is perceived to be negative, an individual may experience anxiety, fear, anger, or frustration - High risk of the community experiencing "collective trauma"
	Resource availability	- Increase job availability in the oil and gas sector	- Decrease in job availability in the tourism industry - Increase in transient workers leading to job loss, hospital availability, food, and water

Table 1 (*Contd.*)

Sustainability pillar	Key theme	Benefits	Costs
			- Potential pollution to water resources can lead to water scarcity
	Well-being	- Based on the Who-5 well-being index, if hydraulic fracturing is perceived as positive, well-being may increase in 40% of questions	- Based on the Who-5 well-being index, if hydraulic fracturing is perceived as negative, well-being may decrease in 80% of questions
Economic	Employment rate	- Increase in jobs in mining, oil, and gas sector	- Negative impact on existing local jobs such as tourism and agriculture
		- Indirect increase in jobs in the transportation, construction, and retail sector	- Jobs could be filled with transient workers instead of local workers
	Local economic activity	- Hydraulic fracturing aids multiple hydrocarbon (crude oil and shale gas) recovery - Increase in demand for equipment and labour - Increase in household income resulting in economic health and increased purchasing power - Increased investment power and higher demand in the housing market - Sale and lease of mineral rights - Economic spill over effect into neighbouring communities	— Potential alteration of landscape could result in the reduction of tourism activities
	Energy price	- Decrease in prices for heating, transportation, and electricity - Improved quality of life - Improved profit margin and job availability in the energy sector	- Costs are underestimated (costs associated with pollution mitigation and public health dealing)
	Energy security	- Not relying on other countries for energy - Energy availability and price stability	- Energy reserves and profits are overestimated by the industry

that is known to face different kinds of pressures from immediate, external and/or complex stakeholders. This analysis was aimed to identify and generate knowledge about the key players in the proposed project. Individuals and organizations of interest were assessed to understand their intentions, concerns, and inter-relationships, to articulate the resources and influences they will contribute to the implementation of the project. This method has been used by many researchers for decision making, policy development, implementation of processes and projects.[63,64] For the purpose of this paper, the stakeholders involved were categorized into two groups, the institution, and the Fylde community. The key players under the institution stakeholders were the corporate investors, government, energy industry, International Oil and Gas Company (IOGC), water company and the media. The Fylde community stakeholders were subcategorized into the working-class group, farmers, NGOs and campaigners, and the vulnerable (children and the elderly).

3.2.2 Prioritization of stakeholders. To prioritize the key stakeholders considered, the power-grid method was used to indicate their level of power and interest (Fig. 2).

3.2.3 Understanding needs of stakeholders. To understand and elaborate on the stakeholders' needs and concerns and the level of assessment required to provide the best and most

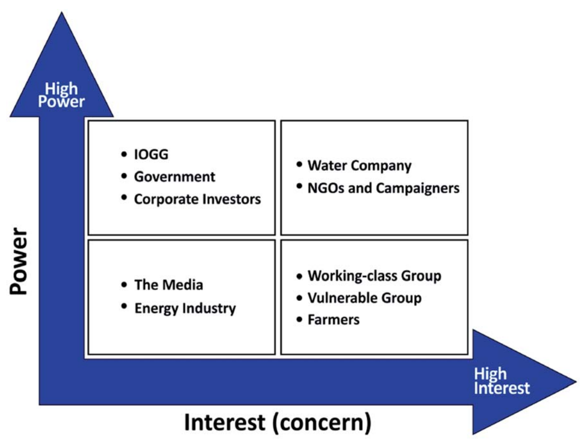

Fig. 2 Power-interest grid of the key stakeholders in the proposed hydraulic fracturing project.

sustainable solutions for a hydraulic fracturing project in the Fylde community, emphasizing the potential impacts on water resources and socioeconomic activities, Table 2 explores the motivations, views, and concerns towards hydraulic fracturing. The findings were drawn from the authors' professional experience and existing literature.[65–68]

3.3 Identification of potential solutions to hydraulic fracturing

Potential solutions are categorized as unique hydraulic fracturing technologies, educational practices, government grants or subsidies, and governmental policies that may improve the current state of hydraulic fracturing. S2 (ESI†) broadly discussed all the identified potential solutions to hydraulic fracturing, which could be integrated with the case-specific solutions to provide robust measures for effective management of all potential hydraulic fracturing activities or shale gas exploitation-related activities in the Fylde community.

3.4 Solution identification and coupled system: DEMATEL method summary

3.4.1 Direct-influence matrix (Z). The direct-influence matrix utilized the information from the three pillars of sustainability from the impact assessment to identify and define the key themes of interest. With the key themes defined, discussions guided by literature occurred, to determine influence levels for each pair of key themes. The pairing and scoring were simply done by matching, assessing, and evaluating the

Table 2 Stakeholder's motivations, concerns, and views

Stakeholder	Power-interest grading in the project	Motivations	Concerns and views
Government	High power-low interest	- To increase indigenous gas production - Reduce energy importation - Create energy exportation - Create jobs	- Agitation from campaigners and community stakeholders
Corporate investors	High power-low interest	- To understand the technology of hydraulic fracturing - Acquisition of interest	- Agitation from campaigners and community stakeholders
IOGC	High power-low interest	- Testing their new technology - Increase revenue - Internalized their brand	- Agitation from campaigners and community stakeholders
NGOs and campaigners	High power-high interest	- Educating the people on the potential impact of hydraulic fracturing - Advocate and monitor policies - Provision of Fylde people's concerns to the international community	- The health and well-being of the people of Fylde - Saving the planet from further degradation
Water company	High power-high interest	- Cheap energy - Increase in portable water demand	- Reduce in water quantity - Fylde aquifer pollution
Media	Low power-low interest	- Creating public awareness for all stakeholders	None
Working-class group	Low power-high interest	- High paying jobs	- Potential increase in rape incidents - Water availability - Infertility - Cancer - Fears of earthquakes
Energy industry	Low power-low interest	- Reduction in energy cost - Job security	- Pollution mitigation costs
Vulnerable group	Low power-high interest	- Reduction in energy cost - Sale and lease of mineral rights	- Cancer - Noise pollution - Reduction in tourism - Water availability - Fears of earthquakes
Farmers	Low power-high interest	- Reduction in energy cost - Sale and lease of mineral rights	- Reduction in water allocation - Polluted air could harm farm animals - Increase in cost of labour - Groundwater and surface water contamination - Noise pollution - Fears of earthquakes

Table 3 The final direct-influence matrix based on literature guided opinions and impacted assessment-based themes and definitions. Purple key themes represent the social pillar of sustainability, blue represents the environmental pillar of sustainability and orange represents the economic pillar of sustainability

Key themes	Physical health	Mental health	Resource availability	Well-being	Water quality	Water quantity	Land use	Wastewater	Air quality	Energy security	Energy price	Employment rate	Local economic activity
Physical health	0	4	2	4	1	2	0	0	0	0	0	3	3
Mental health	4	0	2	4	1	2	1	0	0	0	0	3	2
Resource availability	3	4	0	4	1	4	3	0	1	2	1	3	3
Well-being	4	4	2	0	0	2	0	0	1	1	1	0	2
Water quality	4	4	4	4	0	4	0	0	0	4	3	1	2
Water quantity	4	3	4	3	0	0	0	3	0	2	1	0	4
Land use	2	4	4	4	4	3	0	1	3	0	0	0	4
Wastewater	2	4	2	2	4	4	0	0	0	3	2	1	2
Air quality	4	4	3	4	4	2	0	0	0	0	0	1	3
Energy security	1	2	4	4	4	1	2	2	3	0	4	4	4
Energy price	1	2	4	4	3	1	1	0	4	4	0	4	4
Employment rate	2	4	3	3	2	3	1	0	3	2	2	0	4
Local economic activity	1	2	4	2	3	4	4	4	3	3	4	4	0

importance or influence of one key theme on another. Following eqn (1), it was established that a score of 0 was no influence, a score of 1 or 2 there was an indirect link between key themes, and a score of 3 or 4 there was a direct link. These weightings can be found summarized in Table 3, and short descriptions of the rationale behind each score can be found in S3 (ESI†).

3.4.2 Total-influence matrix and threshold. The direct-influence matrix (Z) was normalized using eqn (2), and the total-influence matrix was then calculated. The result was presented in Table 4. The threshold, which is defined in eqn (6) as α, was then determined by averaging all values within the total-influence matrix to obtain a threshold of 0.13. In other words, based on this case study, any total-influence greater than 0.13 is considered a significant enough influence, and an arrow will be drawn from key theme one to key theme two. However, based on this assessment, there would be 87 influence arrows, which were deemed to be too many to create a legible and valuable coupled system. Instead, it was decided that the threshold would be increased to 0.2, which resulted in 29 influence arrows included in the coupled system diagram.

3.4.3 Influential relation map. First, to construct the IRM, the vectors as defined in eqn (5), R, C, $C+R$, and $C-R$ must be determined to identify the key themes that are in either the

Table 4 The final total-influence matrix derived from the direct-influence matrix. Purple key themes represent the social pillar of sustainability, blue represents the environmental pillar of sustainability and orange represents the economic pillar of sustainability. Light green cells represent significant influence based on $\alpha = 0.13$ and dark green cells represent significant influence based on $\alpha = 0.2$. The dark green cells will be the only influences depicted in the coupled system

Key themes	Physical health	Mental health	Resource availability	Well-being	Water quality	Water quantity	Land use	Wastewater	Air quality	Energy security	Energy price	Employment rate	Local economic activity
Physical health	0.077	0.177	0.122	0.177	0.065	0.117	0.032	0.025	0.035	0.043	0.039	0.123	0.143
Mental health	0.164	0.090	0.121	0.176	0.064	0.115	0.052	0.023	0.035	0.041	0.037	0.120	0.122
Resource availability	0.182	0.223	0.123	0.227	0.095	0.195	0.114	0.040	0.080	0.108	0.081	0.150	0.189
Well-being	0.156	0.166	0.113	0.081	0.040	0.105	0.028	0.022	0.052	0.057	0.054	0.055	0.114
Water quality	0.207	0.226	0.216	0.235	0.072	0.196	0.051	0.039	0.059	0.161	0.131	0.118	0.172
Water quantity	0.182	0.180	0.189	0.182	0.064	0.093	0.044	0.102	0.046	0.103	0.076	0.079	0.188
Land use	0.166	0.225	0.210	0.226	0.160	0.179	0.046	0.060	0.116	0.067	0.059	0.082	0.204
Wastewater	0.151	0.211	0.161	0.174	0.156	0.188	0.043	0.036	0.049	0.136	0.106	0.105	0.156
Air quality	0.191	0.204	0.167	0.206	0.144	0.138	0.038	0.029	0.039	0.056	0.049	0.095	0.163
Energy security	0.166	0.217	0.247	0.264	0.190	0.163	0.107	0.089	0.145	0.093	0.170	0.198	0.241
Energy price	0.155	0.203	0.234	0.251	0.160	0.149	0.082	0.043	0.162	0.170	0.076	0.191	0.230
Employment rate	0.163	0.226	0.194	0.210	0.122	0.177	0.073	0.040	0.126	0.114	0.107	0.090	0.212
Local economic activity	0.176	0.231	0.260	0.235	0.179	0.237	0.152	0.140	0.149	0.166	0.174	0.202	0.168

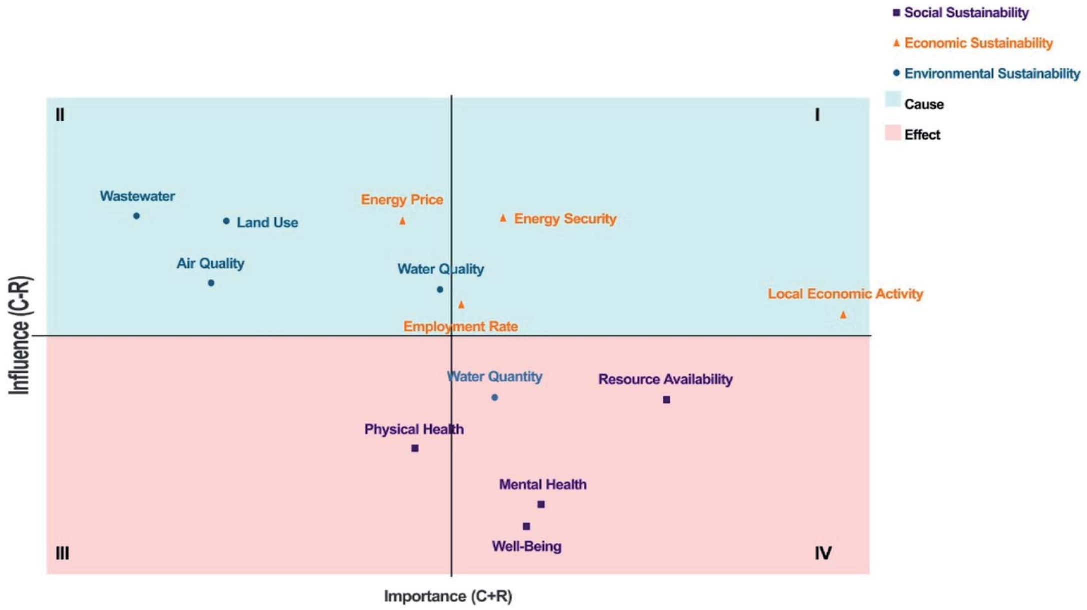

Fig. 3 Summary matrix of importance ($C + R$) and influence ($C - R$). Where the horizontal line is an influence of 0, and the vertical line is the mean importance value (value = 3.4). Quadrant I themes represent key themes that are "core factors" or intertwined givers, Quadrant II themes are driving factors or autonomous givers, Quadrant III themes are relatively disconnected from the system and are independent factors or autonomous receivers, and Quadrant IV themes are intertwined receivers which are impacted by other factors and cannot be directly improved.[18]

Table 5 Numerical summary of importance ($C + R$) and influence ($C - R$) sorted based on the importance level of the sustainability themes

Key themes	C	R	$C + R$	$C - R$	Identification
Local economic activity	2.470	2.300	4.770	0.170	Cause
Resource availability	1.808	2.358	4.165	-0.550	Effect
Mental health	1.160	2.579	3.740	-1.419	Effect
Well-being	1.044	2.644	3.688	-1.599	Effect
Energy security	2.290	1.317	3.608	0.973	Cause
Water quantity	1.527	2.053	3.580	-0.526	Effect
Employment rate	1.855	1.610	3.465	0.246	Cause
Water quality	1.884	1.512	3.396	0.372	Cause
Physical health	1.175	2.136	3.311	-0.961	Effect
Energy price	2.105	1.159	3.264	0.947	Cause
Land use	1.801	0.863	2.664	0.937	Cause
Air quality	1.519	1.093	2.612	0.426	Cause
Wastewater	1.672	0.687	2.359	0.985	Cause

cause or effect group (Fig. 3) (For numerical tabulation, see Table 5). From Fig. 3, the key theme with the greatest impact (Quadrant I) is local economic activity, and the core factors of the system are energy security and employment rate. Within Quadrant II, the driving factors, include water quality, energy price, land use, air quality, and wastewater. These key themes can all be impacted more directly, and will drive the system, but would not be as impacted by other adjustments within the system itself. Physical health, while near Quadrant IV, is the lone theme in Quadrant III, representing the most disconnected theme from this system in the context of Fylde. This may be due to all the indirect influences physical health was expected to have in the direct-influence matrix. Finally, Quadrant IV contains water quantity, resource availability, mental health, and well-being. These themes cannot be directly improved and are mainly dependent on the themes within quadrants I and II. The findings in this section, the total-influence matrix, and the threshold section will determine the final depiction of the coupled system diagram.

3.5 Coupled system

The results of the DEMATEL model were used to construct a coupled system diagram to better illustrate the results and the relationships between the key themes (Fig. 4). The cause-and-effect relationships and the degree of importance were used to illustrate the nodes. The larger "cause" nodes had the greatest number of arrows going out, and the "effect" nodes had the greatest number of arrows coming in. Local economic activity was the biggest "cause" with the $C + R$ value of 4.8 and resource availability was the biggest "effect" with a $C + R$ value of 4.2. The nodes for these two sustainability themes were sketched as the two largest nodes. The medium nodes had a $C + R$ value of 3.5 to 3.7 and the small nodes had a value of 2.4 to 3.4 regardless of "cause" or "effect" status. Each node had a distinct colour to represent its respective pillar of sustainability.

Looking at Fig. 4, the total-influence matrix was used to connect the themes with arrows. The colour of the arrows in the diagram represented the nature of the impact within the themes. A green arrow depicted a positive influence, and a red arrow depicted a negative influence. For example, an increase in local economic activity due to shale gas exploitation using hydraulic fracturing results in an increase in resource availability, and it is represented as a green arrow. However, an increase in energy price due to the absence of shale gas exploitation using hydraulic fracturing results in a decrease in resource availability, and it is represented with a red arrow. The degree of influence from the total-influence matrix was used to categorize the arrows in three weight sizes. All influence values larger than the threshold value of 0.2 were represented as arrows and the other values smaller than the threshold were not sketched to avoid a crowded diagram.

The coupled system diagram illustrated a great number of arrows going out from the economic and environmental nodes and coming in the social nodes. Of all the impacted nodes, resource availability and well-being were the most affected in the context of hydraulic fracturing. However, when choosing solutions, it is important to note the biggest "cause" nodes to ensure effectiveness. Local economic activity, energy security, and water quality had the greatest $C + R$ value as a "cause" node and were used as the primary decision-making strategy for designing the hydraulic fracturing solutions.

3.6 Proposed best and sustainable solutions for Fylde

To provide the best and most sustainable solutions for a hydraulic fracturing project in the Fylde community, a holistic

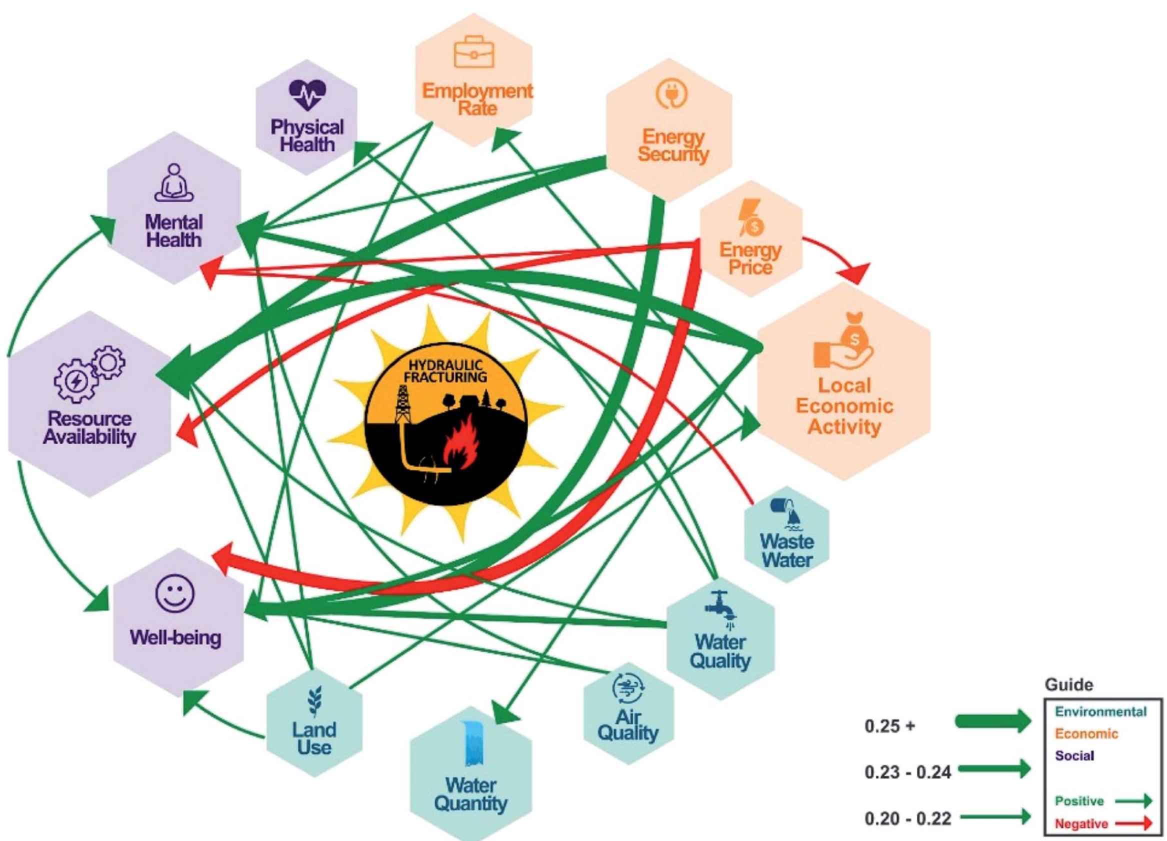

Fig. 4 The result of the DEMATEL model was depicted as a coupled system diagram with the major arrows. The nodes represent all themes of sustainability under study and the size of the nodes represents the degree of impact. The size of the arrows represents the degree of influence. The arrows with the degree of influence under the threshold value of 0.2 are not illustrated.

approach was utilized. Based on the authors' findings, following a robust assessment and evaluation *via* literature review, stakeholder analysis, systems' key themes simulation using DEMATEL, the best and most sustainable solutions were designed to balance the needs of the Fylde community, the UK government, the local water resources, and socioeconomic activities in the surrounding areas. Table 6 shows the proposed best and most sustainable solutions for Fylde, the stakeholders impacted, and the key themes to be impacted positively or negatively, which could be a cause or effect as defined by DEMATEL. The solutions are ranked based on the themes that are impacted. A solution was ranked higher if the themes impacted were a "cause" node or a large $C + R$ value. Solutions were ranked lower if the themes impacted were "effect" nodes or had a low $C + R$ value.

3.6.1 Enhanced hydraulic fracturing technology. This was indicated to be the ultimate solution when considering the Fylde community. Enhanced hydraulic fracturing technology houses several sub-technologies. 3D imaging revolutionized oil and gas exploration and exploitation,[69] and a study by Jia *et al.* indicated that 3D seismic imaging combined with horizontal drilling increased shale gas production in the US by 50%.[70] 3D imaging is one of the most recommendable hydraulic fracturing technologies for the Fylde shale gas exploration activities. 3D imaging can effectively quantify the pore nanostructure of a shale gas formation containing kerogens (organic matter rich in carbon atoms) and estimate gas transport (by assessing the rocks' porosity and permeability). Without a doubt, it could be agreed that this is the key aspect of hydraulic fracturing in the Fylde community as Professor John Underhill, a professor of Exploration Geoscience, stated that "structural interpretations suggest that this particular shale gas reserve, known as the Bowland Shale gas play, remains highly challenged with significant uncertainty in its resource estimates, the planning of well site locations, horizontal wellbore pathways and risk of induced seismicity on faults that are seismically resolvable and those that are sub-seismic scale.".[71] In summary, 3D imaging technology could be considered to bridge the gap of significant uncertainty in resource estimation. Thus, providing a good insight into the economic viability of the Fylde shale gas prior to hydraulic fracturing, thereby mitigating unnecessary environmental and socioeconomic disturbances in the Fylde community.

E-hydraulic fracturing (electric powered hydraulic fracturing) is one of the new technologies in shale gas exploration and exploitation, and it may be one way to reduce greenhouse gas (GHG) emissions in Fylde while exploiting the Bowland shale gas. E-hydraulic fracturing was developed by Halliburton in 2016 and commercialized in 2019.[72] E-hydraulic fracturing works by using wellhead gas to run the gas turbine to generate energy for the system, and as opposed to the diesel-driven pumps in oilfields, E-hydraulic fracturing uses electrically powered pressure pumps.[73] According to Micheal Segura, the senior vice president of the Completion and production Division at Halliburton, E-hydraulic fracturing reduces GHG by 50%.[73] This will significantly reduce the potential impacts of emissions from shale gas hydraulic fracturing exploration and exploitation in the Fylde community.

To protect local water security, StimuFrac was recommended. To better understand how StimuFrac works, think of the pressure one feels when dissolving several crystals of pop rocks in their mouth. StimuFrac is a hydraulic fracturing fluid made up of carbon dioxide and a water-based solution containing polymer. The combination of these two chemical

Table 6 Summary of best solutions for the hydraulic fracturing project in Fylde

Ranking	Proposed solution	Stakeholder(s) impacted	Theme(s) impacted
1	Enhanced hydraulic fracturing technology (3D imaging of kerogen, E-hydraulic fracturing, stimuFrac, on-site WWTP, and carbon capturing technologies)	- IOGC - Community - Corporate investors	- Local economic activity - Water quality/quantity - Energy security - Wastewater - Air quality - Health (physical, mental, well-being)
2	Government funding farmers	- Community - Government	- Resource availability - Local economic
3	Government funding for regulatory body and monitoring equipment	- Government - Community	- Water quality - Health (physical, mental, well-being) - Air quality - Employment rate
4	Policy requiring yearly EA to be publicly available	- IOGC - Community - Government	- Health (physical, mental, well-being) - Water quality/quantity - Wastewater
5	Policy preventing RE-injection of wastewater	- Government - IOGC - Community	- Mental health and well-being - Water quality/quantity - Wastewater
6	Community engagement	- Community - IOGC	- Mental health and well-being

compounds during hydraulic fracturing results in fluid volume expansion with indigenous pressure. Using StimuFrac for the hydraulic fracturing project will reduce water abstraction in the Fylde community and could potentially reduce the operational cost of hydraulic fracturing activities by 60%,[74] thereby increasing energy security.

On-site wastewater treatment plant (WWTP) can encourage water reuse as the flowback fluid and produced water generated during the hydraulic fracturing do not need to be transported to another site (out of Fylde) for treatment and disposal, which could lead to the reduction of water quantity in Fylde. On the other hand, to dispose of the hydraulic fracturing wastewater in the Fylde surface water with the aim of maintaining water quantity requires wastewater treatment to avoid surface water pollution. Hence, on-site WWTP could be recognized as best practice, as this would decrease the need for waste transportation. Furthermore, some of the wastewater treatment chemicals required for the on-site WWTP can be sourced locally, thereby promoting the local economy of the Fylde community.

Carbon capture technologies can be used to maintain and reduce greenhouse emissions while exploiting the shale gas in the Fylde community. Although carbon capture, utilization, and storage (CCUS) is a developing technology and may not yet be profitable and commercialized, the authors confirmed that incorporating the technology while exploiting the shale gas will create more jobs in the Fylde community, thereby improving the local economy. In addition, this technology may reduce air pollution, thereby maintaining/improving air quality. Moreover, the thought of integrating this technology into the shale gas exploitation activities by the Fylde community stakeholders may improve their mental health and changes their overall perspective on the project.

3.6.2 Government grant and funding for farmers. The primary land use in terms of area in the Fylde community is agriculture.[75] Therefore, the UK government providing funds to the farmers can help deliver sustainable farming techniques, such as water harvesting, drip irrigation system, and dry farming. These are proven farming methods recognized as water savers; according to Zhang *et al.*, drip irrigation methods of farming can increase water use efficiency by 17.2%.[76] These solutions could improve local economic activities while enhancing resource availability.

3.6.3 Government funding for independent regulatory body and monitoring equipment. To avoid conflict of interest, the UK government must fund an independent regulatory body to oversee the entire hydraulic fracturing process to ensure that the IOGC activities (exploration and exploitation) fully comply with the UK's environmental policies. As reported by the UK Onshore Oil and Gas, many environmental impact assessment reports seem to prove that other reports are inaccurate, which makes it confusing to the general public. Hence, the importance of an independent regulatory body whose reports won't be altered, thereby improving public trust.[77] In addition, the provision and installation of monitoring equipment and systems, such as a gas meter, sound level meter, and remote-sensing satellite systems, especially in areas close to the hydraulic fracturing site, could greatly benefit the health and safety of the community stakeholders.[78] The monitoring equipment is expected to trigger an alarm in the event of gas leaks. This will help mitigate the potential exposure of the people of Fylde to toxic chemicals associated with shale gas, which could be carcinogenic, mutagenic, or harmful to unborn children. In addition, the installation of the monitoring equipment could provide more job opportunities for the people of Fylde.

Furthermore, the UK government must ensure that there are suitable and up-to-date monitoring techniques and models for minor to major earthquakes. The most associated earthquakes with hydraulic fracturing activities are the induced earthquakes,[79] which normally possess shallower focal depths and are smaller in magnitude when compared to the tectonic earthquakes. Therefore, it is strongly recommended to have a locally calibrated application model for predicting ground motions[79] in the Fylde community to account for any observed Induced seismicity during the shale gas exploitation. Moreover, the authors strongly recommended and emphasized that it is imperative to carefully study and understand hydraulic fracturing-induced earthquakes so as to mitigate extreme reactions (from the environmental, social, and legislative perspectives).[80]

3.6.4 Policy requiring yearly environmental assessment (EA) to be publicly available. Apart from the ground investigation or environmental impact assessment required before the start of the hydraulic fracturing project, it is imperative for the UK government to make it compulsory for the IOGC (in collaboration with an independent agency) to initiate monthly or even weekly environmental monitoring reports, which may include, air quality monitoring and groundwater and surface water monitoring, and a comprehensive yearly report should be provided and made accessible to all the stakeholders, especially the community stakeholders. A study by Purkis *et al.* indicated that environmental monitoring program is something that has not always been available in the context of the US.[81] Therefore, the authors emphasized and indicated that this policy could lead to the improvement of wastewater management, air quality, water quality, and the health and well-being of the Fylde stakeholders (Table 6).

3.6.5 Policy preventing re-injection of wastewater. As discussed in the study literature review (see S1.1.5 (ESI†)), the reinjection of wastewater into the subsurface formation could be said to be the primary cause of minor earthquakes during shale gas exploitation. Moreover, it is noted that a lot of unpleasant things may have been done in the US with respect to re-injection of wastewater into the subsurface as the 2005 Act exempted hydraulic fracturing from being considered an underground injection under the safe water drinking act,[82] preventing hydraulic fracturing from complying with the several regulations to prevent groundwater contamination.[83] Hence, the UK government must ensure it provides and maintain a policy preventing the IOGC from re-injecting wastewater into the subsurface. This could help reduce concerns from the community stakeholders, thereby improving mental health and well-being.

3.6.6 Community engagement. Research by Mactaggart demonstrated that the pathway to a successful project such as mineral extraction is the engagement of community stakeholders and their services.[84] Therefore, the authors strongly recognized that engaging and keeping the community stakeholders up to date would be an essential aspect of the project, especially in building the community's trust. This can be arranged once every month or once every quarter. Another thing that the authors firmly stated could be used to build the community's trust is for the IOGC and the UK government to ensure all the licenses, such as the social license[85] and district political license for hydraulic fracturing operations, are granted accordingly.

Furthermore, community town hall forums will provide a conducive environment for the stakeholders to share their concerns and views and receive immediate feedback. In addition, community town hall forums could be a good place for the IOGC to share most of its operational and other contents, such as standard operating procedures, daily logs, and incident reports, with the local residents and district leaders. This is a good way of keeping the community fully engaged in the project as well as building trust between the stakeholders, especially between the IOGC and the community. Moreover, this solution may ultimately improve the health and well-being of the people of Fylde as it provides the necessary education and information about hydraulic fracturing. Even though this proposed solution is ranked no. 6 in Table 6, due to the key theme impacted (mental health and well-being), as indicated by DEMATEL, and the stakeholders involved, it was recognized by the authors as a highly valued solution to hydraulic fracturing.

4 Conclusions

This study assessed and evaluated the costs and benefits of hydraulic fracturing. The Fylde community was found to be relatively in fuel poverty, predominantly relying on industries such as the aerospace industry and the chemical industry and partially on tourism. In terms of area, agriculture is the major use of land in Fylde, and 57% of its population were of working age. A thorough impact assessment of hydraulic fracturing on the three sustainability pillars (social, economic, and environmental) was conducted to provide a background for assessing the interactions and the feedback loops within and across each sustainability theme. Additionally, all stakeholders involved in the simulated hydraulic fracturing project were identified and categorized based on their degree of power and interest.

The DEMATEL method was successfully utilized through an interdisciplinary approach to model the cause-and-effect relationships between various sustainability themes. The model produced a total-influence matrix and was used to construct a coupled system diagram. The model demonstrated that in a hydraulic fracturing project, all the key environmental elements (water quality, land use, air quality, and wastewater) except water quantity are more likely to be directly impacted, and they are the driving factors of the systems. Local economic activity was found to have the most influence on many different sustainability themes, and resource availability was found to be the most impacted theme. The degree of importance and influence of each theme was used to design effective solutions for a sustainable hydraulic fracturing project.

The suggested solutions which could be combined with other hydraulic fracturing techniques, consisted of enhanced hydraulic fracturing technology, government funding for farmers and regulatory bodies, yearly public environmental assessment reports, implementation of a policy banning the wastewater underground reinjection, and holding town hall meetings to address the community stakeholders' concerns. The coupled system developed in this paper provides a great insight into the interactions and feedback loops between hydraulic fracturing activities and the key themes of the three pillars of sustainability. Thereby indicating patterns and how elements (themes) of the systems may be controlled to execute hydraulic fracturing successfully. Moreover, it also demonstrated that designing sustainable solutions for hydraulic fracturing requires a joint initiative of petroleum engineers, environmental scientists, social scientists, policy makers, and several other stakeholders. The overall result of this paper presented a unique approach to evaluating and selecting appropriate community-specific solutions for sustainable hydraulic fracturing. The developed approach could be used to model other locations aimed for shale gas exploitation activities as well as other related projects such as landfill construction and power station installation projects.

Conflicts of interest

There are no conflicts of interest.

Acknowledgements

We thank Dr Sarah Dickson-Anderson (Professor & Associate Chair – Graduate, Civil Engineering, McMaster University, Canada) for her guidance throughout the period it took the authors to complete this project. The broad and in-depth knowledge provided by Dr Dickson-Anderson and Dr Schuster-Wallace (Associate Professor, Department of Geography and Planning, University of Saskatchewan) on the coupled-systems approach of society, water resources, and environmental sustainability was the nucleus for the success of this paper.

References

1 S. Ahmad, S. Razzaq, M. Rehan, M. Hashmi, S. Ali and Z. Abbas, *International Journal of Renewable Energy Research*, 2019, **9**(3), 1537–1547.
2 R. Avtar, S. Tripathi, A. K Aggarwal and P. Kumar, *Resources*, 2019, **8**(3), 136.
3 A. E. Ladd, *Fractured Communities: Risk, Impacts, and Protest against Hydraulic Fracking in US Shale Regions*, Rutgers University Press, New Jersey, 2018.
4 Z. Asghar, *Applied Econometrics and International Development*, 2008, vol. 8, pp. 167–180.
5 M. Muhammad, R. Aziz and V. Yew, *International Journal of Environment, Ecology, Family and Urban Studies*, 2018, **8**(4), 23–30.

6 European Commission (EC), *Environment Fact Sheet: Industrial Development*, https://ec.europa.eu/environment/pubs/pdf/factsheets/ind_dev.pdf, accessed February 2021.
7 A. Goonetilleke and M. Vithanage, *Water*, 2017, **9**, 281.
8 Z. Kılıç, *The Importance of Water and Conscious Use of Water*, https://medcraveonline.com/IJH/IJH-04-00250.pdf, accessed March 2021.
9 N. Girouard, E. Konialis, C. Tam, P. Taylor, B. Buchner, D. Justus, W. Blyth, I. Barnsley, A. Bromhead, J. Corfee-Morlot, R. Dellink, D. Dorner, R. Gaghen, N. Johnstone, M. Linster, B. Magné, and R. Tromop, Organisation for Economic Co-operation and Development (OECD), *Green Growth Studies: Energy*, https://www.oecd.org/greengrowth/greening-energy/49157219.pdf, accessed February 2021).
10 A. Shubbar, M. Nasr, M. Falah and Z. Al-Khafaji, *Energies*, 2021, **14**, 5896.
11 L. Stamford, *Briefing: Shale gas and the UK's Low Carbon Transition*, http://www.ukuh.org/media/sites/researchwebsites/2ukuh/89490%20SGUK%20Low%20Carbon%20Transition.pdf, accessed December 2021.
12 C. Jia, M. Zheng and Y. Zhang, *Pet. Res.*, 2016, **1**, 113–122.
13 J. I. Andrews, *The Carboniferous Bowland Shale gas study: geology and resource estimation*, https://tcs.ah-epos.eu/eprints/1679/, accessed December 2021.
14 A. Ufimtseva and T. Prior, *China's Arctic Engagement*, 2021, **9**, 264.
15 A. F. Mingazov, K. R. Ibragimov and I. S. Samoilov, *Perspectives for Re-Stimulation of Horizontal Wells with Multistage Hydraulic Fracturing with Ball Arrangements*, One Petro, Russia, 2020.
16 P. Whitelaw, C. Uguna, L. Stevens, W. Meredith, C. Snape, C. Vane, V. Moss-Hayes and A. Carr, *Nat. Commun.*, 2019, 10.
17 Lancashire County Council, *Fylde district*, https://www.lancashire.gov.uk/lancashire-insight/area-profiles/local-authority-profiles/fylde-district, accessed February 2021.
18 F. Council, *Fylde District Profile*, https://new.fylde.gov.uk/wp-content/uploads/2019/07/Fylde-District-Area-Profile-2019-v1.1.pdf, accessed February 2021.
19 B. Penney, *The English Indices of Deprivation 2019*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835115/IoD2019_Statistical_Release.pdf, accessed February 2021.
20 D. Caldwell, *Map and Details for Fylde Borough Council Local Authority*, https://www.geopunk.co.uk/council/fylde-district, accessed February 2021.
21 D. Feher, *England Maps*, https://www.freeworldmaps.net/europe/united-kingdom/england/, accessed February 2022.
22 T. Dixon, *Discover Fylde - Lytham, St Annes and rural Fylde - Visitor Info*, https://www.discoverfylde.co.uk/fylde-villages/, accessed February 2021.
23 B. Council, F. Coast; Highways and and T. Masterplan, https://democracy.blackpool.gov.uk/documents/s4840/Appendix%206a%20Fylde Coast-highways-and-transport-masterplan-draft-.pdf, accessed , February 2021.
24 F. Council, Economic Development Strategy and Action Plan: 2012 – 2030, https://new.fylde.gov.uk/wp-content/uploads/2019/10/ED034-Fylde-Economic-Development-Strategy-and-Action-Plan-2012-2030-2012-.pdf, accessed, February 2021.
25 P. Arye, Average earnings and hours of work, provisional estimates for April 2019, https://www.lancashire.gov.uk/media/910886/average-earnings and-hours-ashe-report-web-final.pdf, accessed , February 2021.
26 E. Health, *Environmental Protection Services*, https://new.fylde.gov.uk/business/environmental-protection/environmental-protection-information/#1521721325726-d86c39a5-ff90, accessed February 2021.
27 R. Beardmore, *'Significant amount' of microplastics washing up on Fylde coast shores*, https://www.blackpoolgazette.co.uk/news/environment/significant-amount-microplastics-washing fylde-coast-shores-3113146, accessed February 2021.
28 The Wyre Rivers Trust, *Wyre Rivers Trust and Wyre Waters Catchment Partnership*, http://www.wyreriverstrust.org/the-river-wyre.html, accessed February 2021.
29 J. Hempstead, *Getting To Know: AFC Fylde*, https://www.pafc.co.uk/news/2014/november/getting-to-know-afc-fylde/, accessed February 2021.
30 Agricultural and Environmental Data Archive (AEDA), *Fylde aquifer/Wyre catchment water resources study*:environmentdata.org, http://www.environmentdata.org/archive/ealit:920, accessed February 2021.
31 F. Council, *Plan for Fylde - Plan for the Future: Fylde Council Local Plan to 2032*, https://new.fylde.gov.uk/resident/planning/planning-policy-local-plan/adopted-local-plan-to-2032/local-plan-to-2032-submission/#1568973478664-ec605e86-07ff, accessed February 2021.
32 B. Purvis, Y. Mao and D. Robinson, *Sustainability Sci.*, 2018, **14**, 681–695.
33 S. Mahmood, N. Jiran, M. Saman and M. Noordin, *Adv. Mater. Res.*, 2013, **845**, 724–729.
34 M. Balane, B. Palafox, L. Palileo-Villanueva, M. McKee and D. Balabanova, *BMJ Global Health*, 2020, **5**, e002661.
35 S. Si, X. You, H. Liu and P. Zhang, *Math. Probl. Eng.*, 2018, **2018**, 1–33.
36 P. Drumond, I. de Araújo Costa, M. Lellis Moreira, M. dos Santos, C. Simões Gomes and S. do Nascimento Maêda, *Procedia Computer Science*, 2022, **199**, 448–455.
37 C. Huang, J. Shyu and G. Tzeng, *Technovation*, 2007, **27**, 744–765.
38 C. Li and G. Tzeng, *Applied Mathematics and Computation*, 2009, **215**, 2001–2010.
39 F. Mactaggart, *MSc thesis*, Technischen Universität Berlin (TU Berlin), 2021.
40 M. Mehany and S. Kumar, *Sustainable Production and Consumption*, 2019, **20**, 375–388.
41 E. Hill and L. Ma, *Science*, 2021, **373**, 853–854.
42 Y. Zhang, J. Mao, J. Mao, A. Chen, X. Yang, C. Lin, Z. Wei, X. Huang, L. Song, F. Tang, Q. Jiang and Y. Ni, *J. Pet. Sci. Eng.*, 2022, **213**, 110422.
43 C. O'Connor and K. Fredericks, *Energy Research & Social Science*, 2018, **42**, 61–69.
44 J. Curries and K. Meckel, *Fracking Has Its Costs And Benefits -The Trick Is Balancing Them*, https://www.forbes.com/sites/ucenergy/

2018/02/20/fracking-has-its-costs-and-benefits-the-trick-is-balancing-them/?sh=77ef3a0619b4, accessed April 2022.
45 M. Golden, *Stanford-led study assesses the environmental costs and benefits of fracking*, https://news.stanford.edu/news/2014/september/fracking-costs-benefits-091214.html, accessed April, 2022.
46 M. Mehany and A. Guggemos, *Procedia Eng.*, 2015, **118**, 169–176.
47 K. Willis, *Thurgood Marshall Law Review*, 2012, **38**, p. 321.
48 W. Sage, *NYUJL & Liberty*, 2017, **11**, 635.
49 Y. Zhang, J. Rupp and J. Graham, *Sustainability*, 2021, **13**, 6650.
50 M. Finkel and J. Hays, *Journal of Epidemiology and Community Health*, 2015, **70**, 221–222.
51 R. Jackson, A. Vengosh, J. Carey, R. Davies, T. Darrah, F. O'Sullivan and G. Pétron, *Annual Review of Environment and Resources*, 2014, **39**, 327–362.
52 K. Black, A. Boslett, E. Hill, L. Ma and S. McCoy, *Annual Review of Resource Economics*, 2021, vol. 13, pp. 311–334.
53 P. Maniloff and R. Mastromonaco, *Resource and Energy Economics*, 2017, **49**, 62–85.
54 J. Hirsch, K. Bryant Smalley, E. Selby-Nelson, J. Hamel-Lambert, M. Rosmann, T. Barnes, D. Abrahamson, S. Meit, I. GreyWolf, S. Beckmann and T. LaFromboise, *International Journal of Mental Health and Addiction*, 2017, **16**, 1–15.
55 L. Dunlop, L. Atkinson and M. Turkenburg-van Diepen, *Children's Geographies*, 2020, **19**, 591–608.
56 N. Apergis, T. Hayat and T. Saeed, *Environ. Sci. Pollut. Res.*, 2019, **26**, 32360–32367.
57 M. Golden, *Stanford-led study assesses the environmental costs and benefits of fracking*, https://news.stanford.edu/pr/2014/pr-fracking-costs-benefits-091214.html, accessed April 22.
58 N. Montcoudiol, D. Banks, C. Isherwood, A. Gunning and N. Burnside, *Acta Geophys.*, 2019, **67**, 365–384.
59 USEIA, *Natural gas explained: Natural gas and the environment*, https://www.eia.gov/energyexplained/natural-gas/natural-gas-and-the-environment.php, accessed April 2022.
60 M. Jiang, W. Griffin, C. Hendrickson, P. Jaramillo, J. Vanbriesen and A. Venkatesh, *Environ. Res. Lett.*, 2011, **6**, 034014.
61 K. Brown, *Report: Shale Supports Massive Air Quality & Public Health Improvements*, https://www.rangeresources.com/report-shale-supports-massive-air-quality-public-health-improvements/, accessed April 2022.
62 NASA, *NASA Study: Rising Carbon Dioxide Levels Will Help and Hurt Crops*, https://www.nasa.gov/feature/goddard/2016/nasa-study-rising-carbon-dioxide-levels-will-help-and-hurt-crops, accessed April 2016.
63 K. Aaltonen, *International Journal of Project Management*, 2011, **29**, 165–183.
64 B. Merrilees, D. Getz and D. O'Brien, *European Journal of Marketing*, 2005, **39**, 1060–1077.
65 M. Heuer and S. Yan, *Sustainability*, 2017, **9**, 1713.
66 M. Cotton, *Environment and Planning A: Economy and Space*, 2015, **47**, 1944–1962.
67 A. Ladd, *Journal of Rural Social Sciences*, 2013, **28**(2), 3.
68 D. Short and A. Szolucha, *Geoforum*, 2019, **98**, 264–276.
69 Dome Energy, *How 3D Seismic Imaging Revolutionized the Drilling Industry*, https://www.domeenergy.com/3d-seismic-imaging-changed-drilling-industry/, accessed April 2022.
70 A. Jia, D. He, Y. Wei and Y. Li, *Journal of Natural Gas Geoscience*, 2021, **6**, 67–78.
71 A. Pugh, *Research Reveals Full Impact of Faulting for Shale Gas Extraction*, https://www.hw.ac.uk/news/articles/2020/shalegas.htm, accessed April 2021.
72 I. Palmer, *Advances in Fracking – Low-Tech, High-Tech, and Climate-Tech.*, https://www.forbes.com/sites/ianpalmer/2022/02/21/advances-in-fracking–low-tech-high-tech-and-climate-tech/?sh=ed8c86d3cdf9, accessed April 2022.
73 S. Whitfield, *Are electrically powered fleets the future of fracking?*, https://www.drillingcontractor.org/are-electrically-powered-fleets-the-future-of-fracking-59560#:~:text=E%2Dfrac%20systems%20utilize%20electrically,that%20may%20otherwise%20be%20flared, accessed April 2022.
74 G. Blankenship, *PNNL Fracturing Fluid: Cost-effective Option for Geothermal Energy*, https://www.pnnl.gov/news-media/pnnl-fracturing-fluid-cost-effective-option-geothermal-energy, accessed April 2021.
75 F. Council, *Fylde Local Plan to 2032*, https://new.fylde.gov.uk/wp-content/uploads/2019/09/SD001-The-Fylde-Local-Plan-to-2032.pdf, accessed December 2021.
76 W. Zhang, J. Sheng, Z. Li, D. Weindorf, G. Hu, J. Xuan and H. Zhao, *Sci. Hortic.*, 2021, **275**, 109728.
77 UKOOG, *UKOOG Response to Chemtrust Report on Fracking*, https://www.ukoog.org.uk/about-ukoog/press-releases/151-ukoog-response-to-chemtrust-report-on-fracking, accessed April 2022.
78 F. Asrar, A. Wen, S. Nasseri, P. Dinas, C. Newman, A. Bukley, K. Crist and D. Irwin, *The Lancet Planetary Health*, 2018, **2**, e469–e470.
79 J. Bommer, B. Dost, B. Edwards, P. Stafford, J. van Elk, D. Doornhof and M. Ntinalexis, *Bull. Seismol. Soc. Am.*, 2015, **106**, 158–173.
80 R. Schultz, R. Skoumal, M. Brudzinski, D. Eaton, B. Baptie and W. Ellsworth, *Rev. Geophys.*, 2020, **58**(3), e2019RG000695.
81 R. Purvis, A. Lewis, J. Hopkins, S. Wilde, R. Dunmore, G. Allen, J. Pitt and R. Ward, *Sci. Total Environ.*, 2019, **673**, 445–454.
82 U. K. Parliament, *Environmental risks of fracking - Environmental Audit Contents*, https://publications.parliament.uk/pa/cm201415/cmselect/cmenvaud/856/85606.htm, accessed April 2022.
83 The Royal Society and the Royal Academy of Engineering, *Shale Gas Extraction in the UK: a Review of Hydraulic Fracturing*, https://www.raeng.org.uk/publications/reports/shale-gas-extraction-in-the-uk, accessed April 2022.
84 F. Mactaggart, *MSc Thesis*, Technischen Universität Berlin (TU Berlin), 2021.
85 R. Boutilier, *A Measure of the Social License to Operate for Infrastructure and Extractive Projects*, https://ssrn.com/abstract=3204005, accessed May 2022.