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Supplementary Information

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

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S1 Sustainability assessment – a comprehensive review

S1.1 Environmental pillar of sustainability

The potential impacts of hydraulic fracturing on the environment could be seen as a problem requiring interdisciplinary study (interactive) and/or multidisciplinary study (holistic). Moreover, it could be considered as a complex human-environment interaction process involving several different expertise and components such as geology, environmental study, ecology, economy, climate study, demography, hydrology, geochemical engineering, or geoengineering, but this is not always the case as the operations and activities involving hydraulic fracturing are typically centered in one academic field.[1] The key environmental receptors prone to the impact of hydraulic fracturing activities are the hydrosphere, biosphere, atmosphere, anthroposphere, and lithosphere, and the major elements associated with these receptors which are considered as the downstream for these impacts include water resources, land, and air.[2, 3]

S1.1.1 Water quantity. In recent times, there have been many questions relating to water resources, exploring the concepts of access to, and remaining quantity of, water.[4-6] Hence, the concerns by professionals and non-professionals on the potential impact during and after hydraulic fracturing activities on water resources can never be underestimated.

One of the major hydraulic fracturing fluids for hydraulic fracturing is water.[7, 8] Therefore, water acquisition is an important aspect that must be emphasized prior to the pre-development of hydraulic fracturing activities. Some of the consideration recommended by USEPA (2015)[9] to be addressed before initiating shale gas development and exploitation are the type and quantity of water that is required to be used for hydraulic fracturing (groundwater or surface water) and how continuous extraction of water may interfere with the quantity of drinking water for the nearby community.

S1.1.2 Water quality. While water quantity seems to be considered most often, it may not always be the most important consideration as the amount of water required for hydraulic fracturing is subject to the subsurface hydrocarbon system (depth of burial, porosity, and permeability) to be fractured.[10] Water quality however is always crucial as treating groundwater to remove pollutants is known to be very difficult, if not unachievable.[11] In principle, one of the greatest potential impacts of hydraulic fracturing on water quality is associated with the concern that hydraulic fracturing could open fractures within the subsurface formation. This could be thousands of feet below the surface, connecting surface waters to shallow aquifers to deep subsurface formations, increasing the risk of hydraulic fracking fluids and formation brine contaminating groundwater.[12]

Furthermore, in the event of leakages and spillages, it could lead to groundwater contamination which will put the community of Fylde at risk as the potable water provided by the Lancashire water company is abstracted from the aquifers in Fylde. In addition, these impacts may be extended to other industries in Fylde, such as the manufacturing companies, as the water allocated to them is used for production activities.

S1.1.3 Land use. Conventionally, shale gas exploitation uses a lot of land due to the drilling of multiple wells.[13] Land use can influence the water quantity of an area as the increase in imperviousness due to the construction of well pads and other hydraulic fracturing facilities reduces stormwater infiltration, thereby reducing groundwater recharge as well as soil hydraulic conductivity.[14] Furthermore, an increase in hard surfaces can increase the quantity and rate of runoff after precipitation, which could lead to flash flooding and erosion, and these could negatively impact surface water due to the introduction of excess suspended solids which are known to have a high affinity to several pollutants.[15]

S1.1.4 Air quality. Several studies on the impact of oil and gas associated activities in the environments have indicated the introduction of non-methane Volatile Organic Compounds (VOCs), such as benzene into the atmosphere.[16-18] These gases may increase air toxicity which could lead to cancer and genetic mutations in humans and animals. As methane is a greenhouse gas, in the event of hydrocarbon spillages and leaks, methane can lead to ozone depletion, thereby increasing the earth's temperature, which could result in excessive evaporation and transpiration resulting in surface water reduction. Moreover, an increase in the earth's temperature can also melt the ice zone (glaciers and sea ice), therefore adding to the rising sea level, which in turn contributes to the elevation of coastal erosion.[19] Oil and gas drilling activities generate a lot of dust, and dust particles are known to be media for the migration of contaminants into the atmosphere, which may result in polluted precipitation and transmission of infectious disease.[20]

For the Fylde community, in the event of hydrocarbon spillages and leaks, leading to an increase in air toxicity, cancer and genetic mutations in humans and animals could become more prevalent. In addition, dust generation during the drilling operations may act as housing agents or media for the ongoing Covid-19 which could lead to an increase in infection rate in the community.[21] These are core aspects to be recognized considering the recorded low fertility rate in the Fylde district.[22]

S1.1.5 Wastewater. Hydraulic fracturing activities generate waste in different states, such as liquid, solid and gas.[23] The major concerns pertaining to hydraulic fracturing are the level of contamination of brine, heavy metals, and radioactive materials in the flowback and produced water (FP), the treatment process, and the available disposal options.[24] Furthermore, in contrast to some opinions that hydraulic fracturing directly causes an induced earthquake, re-injection of wastewater generated from hydrocarbon production has been indicated to be the primary cause of induced

earthquakes which could result in groundwater contamination.[25] In most cases, most of these wastes are disposed of at nearby water bodies and landfill sites.[26] Illegal dumping or incidental discharge of wastewater into the Fylde water body and/or land will lead to land pollution and/or surface water contamination, affecting the community's health and tourism industry.

S1.2 Social pillar of sustainability

The social pillar of sustainability aims to mitigate risks by considering the health and well-being of individuals and communities by understanding what people need from the places they live and work. For this paper, key themes that will be explored are physical health, mental health, resource availability, and well-being. A socially sustainable community and project aims to be equitable, diverse, and provide a good quality of life.[27]

S1.2.1 Physical health. It has been well documented that hydraulic fracturing can have a negative impact on an individual's physical health. Some studies have found that health impacts arisen from air or water pollution due to hydraulic fracturing practices.[28] can lead to mild ailments such as headaches, diarrhea, nosebleeds, asthma, dizziness, and muscle spasms,[28, 29] or more serious complications such as parkinsonism, neuropathy, kidney disease,[30] and cancers[31]. Furthermore, these risks of mild to severe physical health impacts were found to increase for residents living within 1 km from an extraction site,[28, 29] however, past 3 km, studies find a drop-off in physical health risks.[28, 32]

S1.2.2 Mental health. The impact on mental health due to hydraulic fracturing can range from an individual level impact to impacts on an entire community, known as "collective trauma". It has been found that individuals living in a hydraulic fracturing community, if they have negative perceptions of hydraulic fracturing, can experience: anxiety due to potential seismic activity causing property damage, or water quality concerns due to well casing damage;[29] fear regarding outside workers moving into their community potentially resulting in increased crimes rates due to their male-dominated demographic, which can increase the risk to women (increased sexual assaults, prostitution, domestic abuse);[33] or fear regarding the physical health and well-being of themselves and their children. However, if these individuals have a positive perception of hydraulic fracturing (i.e., hydraulic fracturing will bring jobs, prosperity, and resource availability), the mental health impacts were found to be positive, encouraging feelings such as eagerness, being pleased, and hopefulness.[34] Thus, the costs and benefits regarding hydraulic fracturing on an individual can significantly differ depending on the individual's initial perceptions.

Regarding the impact on a community, studies have found that hydraulic fracturing can cause collective trauma. Collective trauma has been defined as "a blow to the basic tissue of social life that damages the bonds attaching people together and impairs the prevailing sense of communality".[35] In one study conducted within the community of Lancashire, due to their collective understanding of the risks associated with hydraulic fracturing and their struggle to impact the decision-making process, the community was left feeling: powerless due to the bureaucratic hoops citizens needed to jump through to make objections; powerless in the face of corporate lobbying; and feelings of depression, a sense of loss, fear, betrayal, guilt, anger, and an emotional rollercoaster as the planning process ebbed and flowed through various planning stages and the appeal process.[28] From this example, it can be extrapolated that similar collective trauma experiences can continue to occur and negatively impact the mental health of entire communities if they are not involved in the application and planning process phases.

S1.2.3 Resource availability. When hydraulic fracturing enters a community, there is often concern regarding the availability of resources due to the potential pollution of current resources and the influx in community members increasing demand on resources. With regards to a loss of resources due to pollution, there is mainly a concern of water security and quality due to hydraulic fracturing fluids potentially contaminating surface and groundwaters. This could result in a potential loss of drinking water and a decrease in the quality and health of fish in the nearby area.[29] With the potential influx of transient workers, communities have also expressed concern about the availability of food, hospital rooms, or housing for community members, leading to resource scarcity.[29] Lastly, job availability is a concern for community members as hydraulic fracturing results in the removal or decrease in the tourism industry, and an increase in oil and gas positions. However, a study has shown that the number of jobs removed is far greater than the number and longevity of the jobs brought in, in addition to the potential of non-community members taking these new positions.[28, 29]

S1.2.4 Well-being. For this paper, the definition of wellbeing will be based on the simple definition of "judging life positively and feeling good".[36] Further, the WHO-5 Well-Being Index quantifies well-being based on a self-assessment of 5 statements: (1) 'I have felt cheerful and in good spirits', (2) 'I have felt calm and relaxed', (3) 'I have felt active and vigorous', (4) 'I woke up feeling fresh and rested', and (5) 'My daily life has been filled with things that interest me'.[35] The WHO-5 will also be considered when evaluating the impacts of hydraulic fracturing on well-being.

Studies have shown that there are several ways hydraulic fracturing can impact the well-being of individuals within the community. Some of the findings show that hydraulic fracturing communities experience: truck traffic and noise pollution which was found to disrupt sleep,[29] is a source of psychological distress, and result in poor academic performance in children;[29] light pollution which can contribute to stress and sleep disruptions;[29] a loss of "peaceful country vistas" potentially resulting in individuals leaving their homes and community;[29] "othering" (us vs. them mentality) due to some of the hopeless feelings within the community leading to fracturing in the community, stress, and feelings of isolation.[36] Thus, for individuals who perceive hydraulic fracturing as negative, it will also have a negative impact on their well-being. Where questions (1) and (2) are impacted by

"othering", (4) is impacted by noise and light pollution, and (5) is impacted by the loss of "peaceful country vistas". Alternatively, those who perceive hydraulic fracturing as positive may feel optimistic,[36] resulting in a high score for at least questions (1) and (5) of the Who-5.

S1.3 Economic pillar of sustainability

Hydraulic fracturing can have a great economic impact on both local and nationwide levels. The assessment of economic impact looks at the potential direct and indirect changes in employment, income, and business activity. It is important to aim for economic growth when proposing a project to improve the standard of living and to allow for population growth. This paper aims to focus on the impact of hydraulic fracturing on employment rate and economic activity at the local scale, and energy security and energy price at the macro scale.

S1.3.1 Employment rate. The employment rate is the proportion of employed people in the labour force, an important indicator of the economy of a country.[37] Unemployment can have adverse effects on the disposable income of households and can result in reduced purchasing power. When purchasing power is reduced, other businesses can lose consumers and more unemployment follows in a cascading manner.[37] Therefore, projects that increase the employment rate are highly beneficial to the economy. A study looked at the impact of hydraulic fracturing on employment in the US across different sectors and reported a 56% increase in Mining, Oil, and Gas sector workers, and a 30% increase in the construction industry workers in counties that had hydraulic fracturing versus those that did not.[38] Looking at the indirect effect of hydraulic fracturing, there was a 25% increase in jobs in transportation and a 5% increase in retail. Several employment and local economic benefits from hydraulic fracturing were indicated in the UK, such as an estimated increase of 30,000 new full-time jobs were predicted to be generated by hydraulic fracturing and the announcement that local authorities can keep 100% of the business rates recovered from hydraulic fracturing sites.[39] However, other factors need to be considered. For example, in assessing the employment rate, it is important to distinguish whether the new jobs are hiring locally or not. In addition, hydraulic fracturing could result in a negative impact on the existing local jobs in other sectors such as tourism and agriculture. Another topic for debate is whether other sources of energy can result in the same increase in the employment rate. A study in the US reported that all non-fossil fuel technologies create more jobs per unit of energy when compared to coal and natural gas.[40]

S1.3.2 Local economic activity. The increase in drilling and hydraulic fracturing activity increases the demand for businesses that provide labor and equipment.[41] Additionally, the health of the local economy improves as the household income of the people involved in hydraulic fracturing and other sectors increases. Maniloff and Mastromonaco reported an 11% increased income in the Mining, Oil, and Gas sector.[38] Other than that, a 5% increase in retail, 8% in construction, and 11% in transportation was reported in the US counties that had hydraulic fracturing versus those that did not.[38] As a result of improved economic health, businesses experience an increasing demand for their goods. The housing market also has been shown to experience higher demand and higher housing prices.[42] An increase in local economic activity can also be seen through the sale and lease of mineral rights for hydraulic fracturing and drilling activities. Furthermore, hydraulic fracturing in one county has been shown to have positive spillover effects onto neighboring counties.[42] Therefore, the benefits are not localized to the hydraulic fracturing county alone.

S1.3.3 Energy price. Looking at the macro scale, energy price is one of the most important topics related to hydraulic fracturing. The global oil demand has been increasing (25% from the year 2000 to 2017) and without hydraulic fracturing, the cost of each US oil barrel would have been 40 to 50 dollars higher.[43-45] The increase in energy price leads to an economic slowdown. The price of residential and commercial heating, transportation and electricity would increase which collectively diminishes the quality of standard of living. However, a reduction in energy price translates into significant cost savings for the energy sector, improving profit margin, and more effective risk mitigation through improved system reliability. Savings on energy prices can also lead to an increased number of jobs in energy supply and related sectors.[38] It is also important to consider all costs when reporting the effects of hydraulic fracturing on energy prices. For example, while energy is produced at a lower price, other costs are increased through factors such as pollution mitigation including wastewater treatment, fines and effluent regulation, and public health dealing costs. These costs could be significant in the context of hydraulic fracturing and should not be overlooked.

S1.3.4 Energy security. Energy security is a broad term but in the context of this paper, it refers to a balanced supply and demand for energy sources, availability, and price stability.[46] Both energy prices and uncertainty in energy lead to high volatility in the economy and it is crucial to invest in energy security.[47] Hydraulic fracturing can impact the energy trade balance in the favor of the hydraulic fracturing country since they are not relying on other countries for energy.[46] This is highly reliant on global politics and any disputes between countries can potentially have significant negative effects on the energy source of the dependant country. Therefore, it is best to increase energy independence as much as possible. However, it begs the question of whether hydraulic fracturing is the solution to energy security. While hydraulic fracturing is reported to contribute to energy security, studies have observed an overestimation of profits and energy production. One study reported that production wells can drop off by 60 to 90% within the first year, decreasing sustainability and stability of energy sources.[48] One of the most debated topics in energy security and hydraulic fracturing is the introduction of renewable sources of energy for a diverse energy portfolio and subsequently, increased energy security. However, it is important to note that with renewable energy technologies, new dependencies on critical materials are introduced and a detailed cost-benefit analysis is required.[49]

S2 Identification of potential solutions to hydraulic fracturing

S2.1 Technologies

The implementation of new technologies can potentially have positive effects on increasing the well production and decreasing the negative environmental impact of hydraulic fracturing. One way to ensure cost-effective hydraulic fracturing is to accurately predict and estimate the long-term oil and gas recovery and extraction prior to drilling. The 3D imaging of kerogen (a source of petroleum and natural gas) has shown proven results in estimating the oil and gas reserves.[50] In addition, kerogen modelling provides accurate insight into the mechanical properties of the hydrocarbons for designing a better hydraulic fracturing process for more effective recovery.[51]

Another important technology is hydro-mechanical modelling of the fractures and predicting the potential seismic activity resulting from the underground wastewater injection. Modelling and simulation of fluid injection have shown to be effective in providing well-specific insight on the chances of induced seismic activity.[52] In addition, using modelling technologies can be a highly effective method for designing the hydraulic fracturing process and should be used to assess the well prior to drilling and hydraulic fracturing.[52]

Technology can also be used for reducing water consumption in the hydraulic fracturing process. Waterless hydraulic fracturing has gained a great amount of attention in recent years to protect water resources. Some waterless technologies include liquid nitrogen,[53] liquid petroleum gas gel,[54] pressurized CO2,[55] and liquefied natural gas[56]. Depending on the available resources, and rock characteristics, a suitable waterless hydraulic fracturing technology can be highly effective. Non-toxic hydraulic fracturing fluids such as CleanStim and StimuFrac can also be beneficial in reducing the harmful risks of an accidental fluid leak and hazardous wastewater production.[57] Another method of reducing water consumption is to implement technologies that allow the reuse and recycling of hydraulic fracturing wastewater. Implementation of an on-site wastewater treatment plant will not only aid in conserving water but will also reduce the negative impacts of wastewater discharge into the environment.[58] In addition, an on-site wastewater treatment plant will reduce the costs of wastewater transport to another facility.

Other notable technologies include hydraulic fracturing with cleaner fuel as opposed to diesel,[59] combining hydraulic fracturing with carbon capture technologies,[60] implementing enhanced methane leak detection,[61] and 3D imaging of formation damage[62]. New advancements in science and technology are constantly being made and making use of them can be beneficial in all pillars of sustainability.

S2.2 Government grants and funding

Government grants and funding are a great tool for promoting the implementation of sustainable solutions.[63] One of the most impactful targets for funding is research.[64] Proper funding of research and development can result in breakthrough innovations, a better understanding of hydraulic fracturing processes, and improved mitigation and remediation of environmental impacts. In addition, it is important to balance the focus of research between increasing the hydraulic fracturing profit and improving environmental sustainability. Other targets for government funding can be towards subsidizing the use of new hydraulic fracturing technologies. Furthermore, proper funding can be implemented for regulatory bodies to ensure that hydraulic fracturing companies are complying with regulations. Government funding for community centers and non-profits in hydraulic fracturing communities can also be a good investment to ensure the well-being of the people near hydraulic fracturing sites.[65] Additionally, grants and funding for farmers in support of agricultural activities can improve resource availability and increase economic activity amongst the local community.[66]

S2.3 Policies

Effective policies and regulations are key to having a sustainable project in any country.[67] In the context of hydraulic fracturing, policies should cover a variety of hydraulic fracturing processes including the amount and source of water used for hydraulic fracturing, the location of the wells to be constructed to protect groundwater and the nearby communities, spill containments and clean-up, management of hazardous waste, treatment, disposal and recycling of the hydraulic fracturing wastewater, control of the underground injection of water to minimize seismic activity, the type of hydraulic fracturing fluid used, and overall pollution monitoring and mitigation. Other impactful policies should be in place to ensure that hydraulic fracturing companies conduct a townhall meeting to adequately intimate interested parties and stakeholders in the community of the project (hydraulic fracturing) status and environmental assessment reports prior to, during, and after hydraulic fracturing to continuously confirm the safety of the project.

S2.4 Education

To make knowledgeable decisions, it is important to have the correct education with regard to hydraulic fracturing. People's knowledge, beliefs, and attitudes towards hydraulic fracturing is a key factor in decision making and project support.[68] Hydraulic fracturing is a highly controversial and politicized topic, and it is important for hydraulic fracturing companies to conduct townhall meetings to address the community's concerns. In addition, the government can play a role in providing the correct information on the true costs and benefits of hydraulic fracturing in the local community to combat reports of overestimated hydraulic fracturing profits and underestimated environmental and social impacts.[69]

In addition, the correct education and training of staff and hydraulic fracturing workers is important in minimizing potential human errors and risks. Hydraulic fracturing involves many human dependant factors, and any errors can have significant human safety and environmental implications.[70] Therefore, a thorough understanding of risk sources and staff training is key to significantly minimizing human errors.

S3 Direct-influence matrix rationale

Table S3.1 - S3.13 provide the reasons or logical basis behind the point scoring used by the authors for the simulation of the DEMATEL model.

Table S3.1 The impact of physical health on:

Influence	Factor	Reason
4	Mental health	Direct effects are observed.
2	Resource availability	Physical health can result in change in resource use for water, food, hospital beds, etc.
4	Well-being	Referring to the definition of WHO, better physical health results in feeling good, fresh, rested, and content.
1	Water quality	Bad physical health and septic tank use plus leakage can have negative effects on water quality.
2	Water quantity	Health has an effect on how much water is used.
3	Employment rate	Good physical health is required for employment.
3	Local economic activity	Good physical health is required for conducting businesses and contributing to the local economic activity.

Table S3.2 The impact of mental health on:

Influence	Factor	Reason
4	Physical health	Direct effects are observed.
2	Resource availability	Mental health can result in change in resource use for water, food, hospital beds, etc.
4	Well-being	Referring to the definition of WHO, better mental health results in feeling good, fresh, rested, and content.
1	Water quality	Mental health can indirectly impact how an individual views and respects water.
2	Water quantity	If one feels fearful for water scarcity, one would be more mindful of how much water is used and try to conserve water.
1	Land use	If one feels fearful for land use change, one will be more mindful of how land is used.
3	Employment rate	Good mental health is required for employment.
2	Local economic activity	Good mental health is required for conducting businesses and contributing to the local economic activity (not as directly as physical health)

Table S3.3 The impact of Resource availability on:

Influence	Factor	Reason
3	Physical health	Resources are needed for living a healthy life.
4	Mental health	Lack of resources induces anxiety
4	Well-being	Referring to the definition of WHO, availability of resources results in feeling good, fresh, rested, and content.
1	Water quality	Availability of resources affects water treatment capacity.
4	Water quantity	Water is a resource
3	Land use	Lack of resources such as food results in land use change to farmlands. Lack of resources such as hospital beds results in land use change to more hospitals.
1	Air quality	Indirect effect through change of land use
2	Energy security	Lack of resources can result in decreased energy production.
1	Energy price	Indirect effects through lack of energy production (low supply results in high prices).
3	Employment rate	Lack of resources can result in a decrease in available jobs in some sectors that need those resources, and can increase jobs in sectors that create those resources
3	Local economic activity	Resources are needed for conducting businesses, tourism, etc.

Table S3.4 The impact of Well-being on:

Influence	Factor	Reason
4	Physical health	Direct effects are observed
4	Mental health	Direct effects are observed.
2	Resource availability	State of well-being can result in change in resource use for water, food, hospital beds, etc.
2	Water quantity	State of well-being affects how much water is used.
1	Air quality	State of well-being can affect the amount of travelling and transportation.
1	Energy security	State of well-being affects how much energy is used.
1	Energy price	Indirect effects through amount of energy used (high demand results in high prices).
2	Local economic activity	Feeling good and content contributes to more economic activity and vice versa.

Table S3.5 The impact of water quality on:

Influence	Factor	Reason
4	Physical health	Direct impact
4	Mental health	Direct impact
4	Resource availability	Water quality impacts the amount of water available for resources such as food, drinking, healthcare.
4	Well-being	Better water quality results in feeling good, fresh, rested, and content.
4	Water quantity	Water quality impacts the amount of water available for use.
4	Energy security	More energy is needed for improving water quality.
3	Energy price	Higher demand on energy for improving water quality (increased demand results in higher energy prices).
1	Employment rate	Indirect effect through physical health.
2	Local economic activity	Indirect effect through physical health. Clean water is required for many businesses.

Table S3.6 The impact of water quantity on:

Influence	Factor	Reason
4	Physical health	Water is required for drinking, sanitation, etc.
3	Mental health	Water is required for recreational, cultural, and spiritual reasons.
4	Resource availability	Water is a resource.
3	Well-being	Better water quantity results in feeling good, fresh, rested, and content.
3	Wastewater	More available water results in more water use and more wastewater generation.
2	Energy security	Lack of water results in negative impact on energy production.
1	Energy price	Indirect effects through lack of energy production (low supply results in high prices).
4	Local economic activity	Water is required for businesses, manufacturing, tourism, etc.

Table S3.7 The impact of land use on:

Influence	Factor	Reason
2	Physical health	Change in land use can cause flooding.
4	Mental health	Depending on the change in land use, it can have positive or negative mental health effects.
4	Resource availability	Direct effects.
4	Well-being	Depending on the change in land use, it can have positive or negative well-being impact.
4	Water quality	Amount of water needed depends on the type of land use.
3	Water quantity	Imperviousness reduces water infiltration, resulting in less groundwater recharge and affects water cycle.
1	Wastewater	Amount of wastewater produced depends on the type of land use.
3	Air quality	Impermeable land is correlated with transportation and lack of vegetation which affect air quality.
4	Local economic activity	Sale/lease of mineral rights, tourism.

Table S3.8 The impact of wastewater on:

Influence	Factor	Reason
2	Physical health	Wastewater from hydraulic fracturing can cause earthquakes.
4	Mental health	The fear caused by potential earthquakes has a negative impact.
2	Resource availability	Affects the amount of water available as a resource.
2	Well-being	Indirect effect through physical and mental health.
4	Water quality	Direct effect.
4	Water quantity	Direct effect.
3	Energy security	Indirect effect through water quality.
2	Energy price	Indirect effect through water quality.
1	Employment rate	Could create jobs for wastewater treatment.
2	Local economic activity	An increase in demand for equipment and labor for wastewater treatment.

Table S3.9 The impact of air quality on:

Influence	Factor	Reason
4	Physical health	Direct effect.
4	Mental health	Direct effect.
3	Resource availability	Increased need for hospital beds and resources for healthcare if air quality is decreased.
4	Well-being	Air quality has direct effects on how one feels.
4	Water quality	Air pollution can result in acid rain and pollutants entering water through precipitation.
2	Water quantity	Bad air quality can negatively affect climate change and precipitation.
1	Employment rate	Indirect effect through physical and mental health.
3	Local economic activity	Can result in lack of tourism and people moving in.

Table S3.10 The impact of energy security on:

Influence	Factor	Reason
1	Physical health	Indirect effect through energy price.
2	Mental health	Indirect effect through energy price.
4	Resource availability	Energy security is directly correlated with how much resources are available. Energy availability and stability result in more resources.
4	Well-being	Direct effect on quality of life.
4	Water quality	Water treatment and pollution mitigation requires energy.
1	Water quantity	Indirect effect through water quality.
2	Land use	Energy security can affect the type of land use (land used for energy production or not).
2	Wastewater	Energy security ensures the availability of energy for wastewater treatment facility operations.
3	Air quality	Availability of energy can result in more transportation.
4	Energy price	Direct effects.
4	Employment rate	Can create jobs in energy sector or impact jobs in other sectors such as tourism and agriculture.
4	Local economic activity	Energy is needed for businesses and manufacturing.

Table S3.11 The impact of energy price on:

Influence	Factor	Reason
1	Physical health	Higher energy price can indirectly affect physical health.
2	Mental health	Higher energy price can indirectly affect mental health. Can create anxiety. Indirect effects through well-being.
4	Resource availability	The price of energy is directly correlated with how much resources are available. Lower energy price results in increased purchasing power and decreased production cost.
4	Well-being	Direct effect on quality of life.
3	Water quality	Lower energy price results in a more cost-effective water treatment.
1	Water quantity	Indirect effect through water quality.
1	Land use	Indirect effect through energy security.
4	Air quality	Decreased energy price can result in more transportation.
4	Energy security	Direct effect.
4	Employment rate	Can create jobs in energy sector or impact jobs in other sectors such as tourism and agriculture.
4	Local economic activity	Lower energy price results in increased purchasing power, higher income, more investments, and lower costs for businesses.

Table S3.12 The impact of employment rate on:

Influence	Factor	Reason
2	Physical health	Indirect effects through mental health and income.
4	Mental health	Direct effects.
3	Resource availability	More jobs result in uptake of more resources.
3	Well-being	Direct effects on how one feels.
2	Water quality	Increased employment rate could potentially result in increased water use and decreased water quality.
3	Water quantity	More employees result in an increase in demand for water.
1	Land use	Depending on the type of land use, jobs can be affected.
3	Air quality	Employment correlates with transportation.
2	Energy security	Jobs can increase energy use.
2	Energy price	Jobs can increase energy demand and increase energy prices.
4	Local economic activity	Direct effects on purchasing power, disposable income, and business growth.

Table S3.13 The impact of local economic activity on:

Influence	Factor	Reason
1	Physical health	Indirect effect through mental health.
2	Mental health	Economic activity such as tourism can affect mental health.
4	Resource availability	Direct effects.
2	Well-being	Indirect effect through physical and mental health.
3	Water quality	Economic activity can affect water quality through businesses such as manufacturing, etc.
4	Water quantity	Water is required for many businesses.
4	Land use	Land use is a direct effect.
4	Wastewater	Economic activity can produce wastewater.
3	Air quality	Economic activity can affect air quality through businesses such as manufacturing, transportation, etc.
3	Energy security	More economic activity increases energy use and increases energy demand.
4	Energy price	More economic activity increases demand on energy which results in higher energy prices.
4	Employment rate	More economic activity can result in more jobs.

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