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ORIGINAL ARTICLE

Energy Demand Reduction: supply chains and risk analysis

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Abstract Demand Reduction is a strategy with the potential to make a significant contribution to the energy supply/demand balance. Its two major themes are improving the energy efficiency of devices (appliances and processes) and changing people's behaviour towards using less energy. In our analysis of a nation's energy security, we treat Demand Reduction as an additional fuel which delivers 'negafuel', allowing a particular level of energy services to be met at a lower volume of supply than would be possible in its absence. In common with other fuels, negafuel is delivered by a supply chain with linked stages, all encountering risks of various types. A comprehensive survey of these risks in a case study of the UK shows that Demand Reduction belongs to a middle-ranking group of fuels in terms of overall risk. High-level risks encountered include the difficulty of assessing and delivering potential energy savings, the rate of building construction at the highest energy efficiency standards, optimism bias, changing policy and regulation, and operational failure (both of technology and policy). Assessing the risk of Demand Reduction as a supplied negafuel focuses attention on specific risks requiring mitigation, facilitating design of better policy, and more effective commercial products.

Keywords Energy conservation · Energy efficiency · Energy saving · Energy security · First fuel

Introduction

Since the oil crisis of 1973 disrupted supplies of middle eastern crude, energy efficiency/saving has been an important theme for research and public campaigns, emphasising the role it plays in enabling supply to match demand. Energy efficiency was described as "*our most underrated energy resource*" (Ross & Williams, 1976) and termed 'the fifth fuel' in the 1980s, after coal, oil and gas, nuclear, and renewables. More recently, the group of activities, processes, and technologies which comprise the energy efficiency/saving has been promoted to being 'the first fuel' (IEA, 2013; Yergin, 2011). A distinction can be drawn between energy efficiency/saving and energy conservation (Boardman, 2004; Karunathilake et al., 2018). Conservation reduces the envelope of total energy demand, being the cumulative effect of energy efficiency/saving, accounting for rebound effects (Brockway et al., 2021; Sorrell, 2009). The energy hierarchy (Arbon, 2012) also draws a distinction between energy conservation and efficiency, but

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places conservation above efficiency rather than treating efficiency as a component. Our broad definition of Demand Reduction (DR) incorporates both the use of devices and behaviour change—the alteration of the way society and individuals use energy (Arbon, 2012; Iweka et al., 2019; Seligman et al., 1978; Staddon et al., 2016; Steg, 2008). Energy saving now includes a set of technologies and services enabling automatic control of devices with different timescales of response. Terms and techniques have emerged such as demand-side response (Gyamfi et al., 2013; Parrish et al., 2020) and demand-side management (Darwazeh et al., 2022), including metering and control, which can be considered under the umbrella of DR insofar as they lead to a reduction in energy demand.

Calculations by the IEA for a group of eleven large economies in the 35 years following 1973 show that energy use grew by 65% less than it would have done without the contribution of energy efficiency (IEA, 2013). In developing policy for improving sustainability, particularly in the light of climate-related goals, the strategy of energy saving focused on making appliances and processes more energy efficient (Pye et al., 2021). Pye et al. draw attention to the neglect in current energy modelling of a range of demand-side options such as reducing demand through lifestyle or behavioural change—how society makes use of energy services. Possibilities include rethinking business practices to extend the useful life of products and reduce resource consumption (Clift et al., 2022), greater use of teleworking (Hook et al., 2020), the design and use of buildings (D'Oca et al., 2018). Steinberger et al., (2009) remark that "*Energy services are the correct conceptual framework to study energy demand*", advocating transition to a performance-based energy economy. However, the necessary business models have been slow to emerge due to various barriers and the lack of appropriate policy (Brown et al., 2022).

Sorrell, (2015) notes that *"Reducing energy demand may prove more difficult than commonly assumed"*, since orthodox economics may have underestimated the need for increasing energy consumption to support economic growth. Sorrell also comments that policy remains largely focused on energy supply and incremental changes within existing systems. He advocates policy interventions to encourage more energy-efficient choices and more support for new energy-efficient technologies. Some of the rapid and large-scale changes needed in the sociotechnical systems that provide energy services are described in more detail by Barrett et al., (2022), who report a UK modelling case study that, utilising the full potential for improvements, could reduce energy demand by 2050 by 52% compared to that of 2020. If such Demand Reductions could be achieved across similar energy economies, it would be much easier to meet global climate goals for carbon dioxide emissions. Chowdhury et al., (2018) list both drivers and barriers to energy saving by industry, categorised as due to market-related factors, organisational and behavioural factors, and policy factors; a number of these may be interpreted in terms of risks which might restrict the contribution that Demand Reduction could make.

The provision of energy requires a supply–demand balance, so the analysis of the complete energy system needs somehow to include DR in the same framework as fuels used to provide primary energy. It would be possible to consider DR as part of each individual fuel supply chain (oil, gas, wind, etc.), implying that every energy systems manufacturer, service provider, distributor, and user of that fuel should consider a lack of DR activity as another cause of risk. However, this would lose the coherence that DR programmes should have, as part of the system delivering energy services to consumers (e.g. heat, light, mobility). Furthermore, relating DR always to the supply chains of other fuels would divert discussion of risks towards the supply side which has long dominated the debate about energy security. Those operating the supply chains of individual fuels have little enough incentive to reduce the volumes being sold, yet DR has significant value with its role in reducing resource consumption and carbon emissions (Steinberger et al., 2009).

We therefore propose to include energy Demand Reduction in an analysis of the energy system, representing it as a separate supply chain, additional to the chains supplying conventional fuels. In the DR chain, various stakeholders undertake a series of activities which can be conceived as three distinct (combined) conceptual stages: measuring the potential for Demand Reduction—creating devices, services, and communication campaigns—operating devices and social practice. DR brought about by this supply chain enables provision of the required level of energy services using a lower volume of supply than would otherwise be the case. This reduction in demand can be considered a ‘negative fuel’—negafuel—comprising two elements: energy efficiency through use of or redesign of devices (appliances and processes) and change in behaviour by people. A related concept of the ‘negawatt’ has been most readily associated with reducing electricity demand through efficiency gains (Lovins, 1990). Recently, possible futures of the smart grid (Balta-Ozkan et al., 2020) suggest new functionalities (Xenias et al., 2015) including negawatt trading (Tushar et al., 2020) using various peer-to-peer mechanisms (Xia et al., 2023). However, the negawatt concept does not easily encompass the wide range of activities constituting DR nor the provision of energy through the supply of molecules (gas or liquid) for transport or heat.

Demand Reduction has the potential to transform the energy economy, but the path to achieving it carries risk. Even when risk is not mentioned explicitly by commentators, descriptors such as ‘difficulty’, ‘problematic’, ‘barrier’, ‘uncertainty’, or ‘issue’ can indicate its presence, where it suggests a possibility that the activity might not occur, or might fail to achieve its goal. This is consistent with the definition of risk as “Exposure to the possibility of loss, injury, or other adverse or unwelcome circumstance” (*Oxford Dictionaries*). Our aims in this work are to demonstrate a method to measure the risk present in programmes to promote Demand Reduction, and through a case study show how the assessment of risk could help in the formulation of relevant policy. The framework provides for the comprehensive screening of all activities in the supply chain against a range of risks in the categories of economic, environmental, innovation, manufacturing, political, skills, and technical. A wide variety of literature dealing with DR in the UK provides evidence for our assessments of risk severity.

Background to the UK case study of DR

We review the successes and failures of the various forms of Demand Reduction as they relate to the UK. Eyre, (2011) notes that one of the main difficulties in reducing demand is that the cost savings accrue to the individual consumer, but the reduction in carbon is to society as a whole because carbon is not adequately costed. The energy efficiency of homes and businesses is in part about the interaction of technical innovations and the willingness of people to adopt them, and adapt their behaviours. For example, the innovation of automatic defrosting of freezers does not save energy, but does save time (Shove & Southerton, 2000), while Lo Piano & Smith, (2022) review the possibilities for residential flexibility and the time shifting of energy demand.

Other claims made for improving energy efficiency include reducing energy poverty and GHG emissions, and improving thermal comfort, health, well-being, energy security, and economic productivity (POST, 2017). A useful overview of the relevant UK policy since the early 1970s is given in Mallaburn & Eyre, (2014), and Hanmer & Abram, (2017) stress the need to learn lessons from previous societal transitions, e.g. moving from using coal to natural gas for heating homes. Most studies on DR are for buildings (Palmer & Cooper, 2014), but also of importance are industrial processes (Griffin et al., 2016, 2017, 2018) and heat (DECC, 2013a; Delta Energy & Environment, 2012; Eyre, 2011). Monahan & Powell, (2011) claim that reducing heating demand will have the greatest effect on reducing GHG emissions.

A synthesis report compiled by DECC, (2013b) suggests that interventions in the home may save between 1 and 10% depending on the sophistication of the scheme, and Rosenow et al., (2018) claim that through a combination of current technologies—including energy efficiency—a 50% saving could be made. It is estimated (LCICG, 2016a) that a total of 64 $MtCO_2$ (by 2050) could be saved in residential buildings. A potential saving of 7% of household electricity use could be made by eliminating the stand-by mode of devices (Coleman et al., 2012). Shove, (2003) contends that the population desires convenience which happens to demand energy. Recent detailed studies have shone light on household activities, practices, and the enabling products (Butler et al., 2016) which gradually become normalised (Shove & Southerton, 2000). As practices change there is a ratcheting-up of demand which acts to recalibrate societal expectations (Shove, 2003). A meta-study for DECC (RAND Europe, 2012) drew three conclusions as follows:

1.programmes combining information feedback on comparative consumption alongside energy efficiency advice did lead to residential DR,

2. awareness of pre-intervention consumption had a statistically measurable effect on the level of energy saving (independent of other factors), and
3. the structure and level of personalisation of the intervention affect the level of energy saving.

However, the provision of information alone is insufficient (Busic-Sontic et al., 2017; Lange et al., 2014) which is described as the 'information-involvement gap' (Axon, 2017). Its importance is noted (Bright et al., 2018) in deep retrofit of mixed tenure tower blocks in particular. Trust has emerged as an issue in the design of programmes for DR, e.g. energy advisors (Owen et al., 2014) and government and businesses (Cotton et al., 2016). However, work on residential consumers (Volland, 2017) indicates that greater trust in institutions is associated with lower energy use and a greater tolerance to risk is associated with higher energy use, and the trust engendered by community groups is demonstrated by Vita et al., (2020).

A group of reasons for the lack of engagement with DR can be described as cultural. Conservatism is observed among professionals and customers in the house building (Heffernan et al., 2015; LCICG, 2016a), commercial building (LCICG, 2016b; Scrase, 2001), and the industrial sectors (LCICG, 2012). A particularly poorly understood factor is that of conspicuous consumption (Hards, 2013). Consumers may want to avoid the stigma of being labelled as "*stingy*", or may prefer high-use devices such as tumble dryers to mitigate the risk of visitors being faced with an unsightly scene. The social gains of, say, a new kitchen outweigh those of energy saving measures (Dowson et al., 2012). Olaniyan & Evans, (2014) suggest that for policies to tackle DR successfully, they must address behavioural and lifestyle and, in addition, cultural factors (Ivanova et al., 2020).

In the policy-making process the ability to use research feedback requires robust assessment of pilot and other schemes (Boardman, 2007a; Heffernan et al., 2015), but such assessments are contextual for both consumers and policy-makers. Boardman, (2004) notes that weak efficiency standards have long-term effects as devices take many years to exit the stock, and stricter regulation would be a driver to increase energy efficiency and increase market opportunities (Stiehler & Gantori, 2016). This led Gavin Killip to call for a regulatory body to draw together training, standard setting, and compliance for the house-building sector (Killip, 2013). Looking to the second half of this century there is uncertainty in the amount of cooling demand for dwellings due to climate change (Gupta et al., 2015), affected by device efficiencies and the thermal performance of buildings.

In their international comparison of measures and policies the IEA (2017) claims that energy efficiency has improved the economic competitiveness of energy-intensive industries, but it is worth noting that the payback period is crucial for industry (Eiholzer et al., 2017). The expected return-on-investment periods for efficiency projects in industry are short—perhaps one to two years. If the payback is quick there is no risk of lack of access to capital, but for longer than, say, three years, it will be very difficult to raise the required investment.

A principal source of energy demand is transport. Low-carbon transport cannot be realised by technology alone (Upham et al., 2013), yet policy remains focused on technology innovation and not on transport and mobility as a service. Furthermore, the widely discredited 'predict and provide' model persists in government policy albeit sometimes disguised (Goulden et al., 2014). When considering innovation in transport planning to reduce energy use, Banister & Hickman, (2013) recommend the use of robust scenario methods at all stages of decision making and policy planning. However, these principles are not applied universally—in the policy context, this can be considered an example of weak technology transfer.

In their extensive review of energy system scenarios, Skea et al., (2021) note the inclusion of energy efficiency gains; however, this is usually as an assumption or modelled in a superficial manner. Demand Reduction is frequently overlooked in UK energy scenarios (Axon & Darton, 2023), though notable exceptions are those devised by the UK Energy Research Centre (Ekins et al., 2013; Skea et al., 2011) and National Grid, (2022).

Methodology

We treat DR, like other fuels, as having a supply chain, in the sense that it results from a series of activities undertaken in a particular order by the stakeholders. For example, smart meters were conceived as a way of reducing energy costs for UK

Table 1 Process stages for DR and a description of the activities which characterise them

Stage	Activity
1. Explore	Measure potential
2. Exploit 3. Condition	Create devices, services, and communication campaigns
4. Convert 5. Distribute 6. Use	Operate devices (electrical, heat, vehicles) or social practice

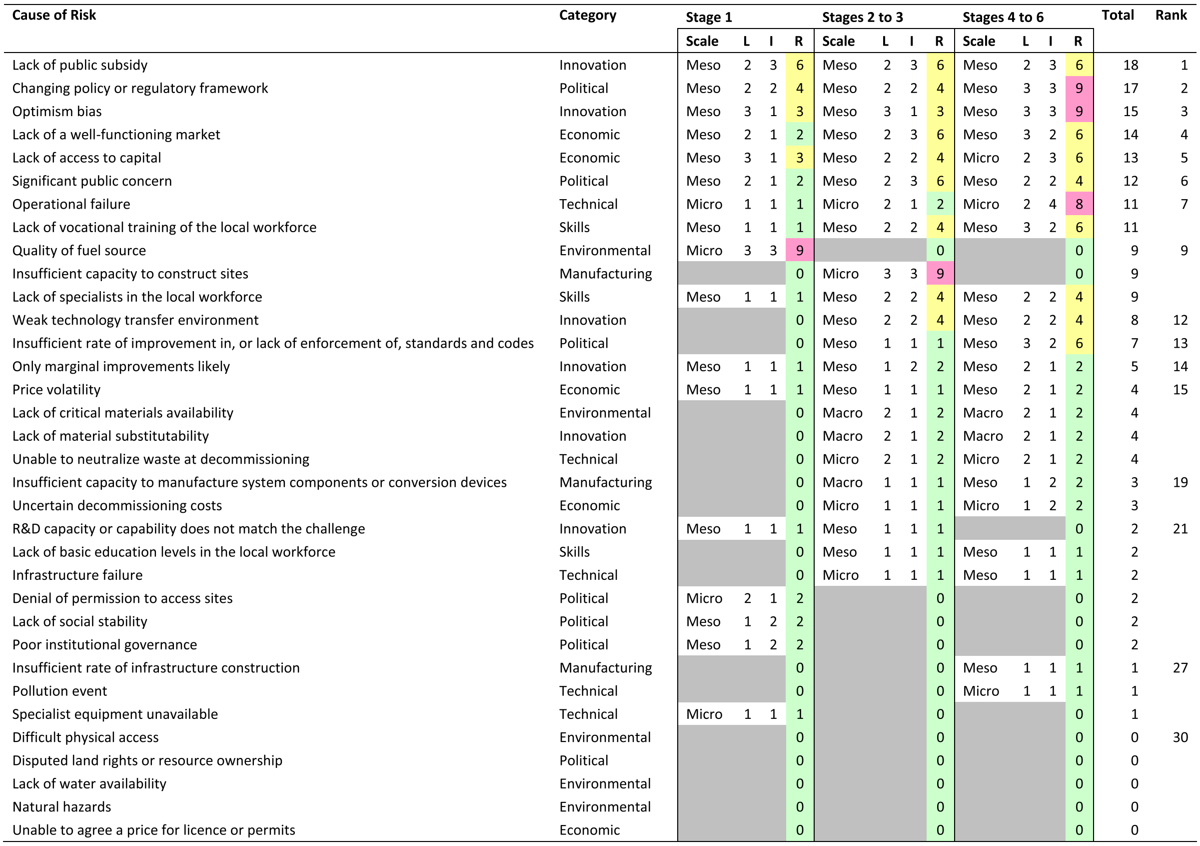
consumers by giving real-time information about energy use. The chain of activities that we treat as a 'supply chain' in this case is as follows: pilot studies and academic investigation suggest the scale of the potential energy savings—go-ahead is given by government to roll-out smart meters to all UK households—meter manufacturers devise and supply the appropriate equipment—installers are trained, and the replacement meters are fitted—the householder uses the in-home display to take various steps to reduce their energy use. These activities are intended to lead to a reduction in demand and can therefore be considered comprising a typical negafuel supply chain.

To enable comparisons with fuels on the supply side of the energy balance, the series of activities directed at reducing energy demand is considered a sequence of six stages: exploring, exploiting, conditioning, converting, distributing, using (Axon & Darton, 2021a). For some fuels some consecutive stages may be combined, and this is the case with DR. By generalising the activities for all DR supply chains, we obtain the descriptions in Table 1.

The stages for DR are less distinct than for other fuels (Axon, 2019), and their aggregation can be thought of as follows (Table 1). Exploration (stage 1, measuring potential) identifies the amount of DR which could be obtained by a particular intervention; it includes, for example, public/consumer surveying or the theoretical modelling of energy efficiency devices or processes and similar investigations. Stages 2–3 (exploit and condition the fuel) develop the instruments (devices, services, or campaigns) by which users can achieve DR. Activities include pilot studies, the planning (or modelling) of major activities, and testing energy efficiency devices/processes at the research stage of development. Stages 4–6 (convert, distribute, use) see the deployment of the DR intervention in the market place. Inevitably there is blurring at the interfaces between stages, reflecting the nature of social systems. Furthermore, explicitly incorporating social practices in our assessment leads to considering the lack of take-up or the rebound effect (Sorrell, 2009) a 'technical failure'.

All activity carries risks, and whether these are trivial or significant is important for analyses such as energy security. We aim to provide a comprehensive and self-consistent system view, incorporating all significant causes of risk that are applicable to the complete range of fuels used by a nation, for all purposes and applications (Axon & Darton, 2021a). The risks were identified using a modified Process Analysis Method (Axon, 2019; Darton, 2017; Smith et al., 2013) for discovering sustainability indicators. The process analysis method identifies impacts (associated with causes of risk in the modified method) and links each to a decision, policy, or practice generating the impact, and to an entity (person or group) receiving the impact. The causes of risk were found using an extensive literature study (Axon & Darton, 2021b) yielding a total of 34 generic but distinct potential causes of risk which are listed in Fig. 1. These causes of risk can be conveniently classed in seven categories: economic, environmental, innovation, manufacturing, political, skills, and technical. For each category we compose a description of the desirable state of the energy system and typical causes of risk to help identify the relevant risks at each stage of a specific fuel supply chain.

Severity of each identified risk is scored by considering its likelihood of occurring (L) and its impact if it does (I). Then Risk = $L \times I$, following the rules for risk matrices (Baybutt, 2016; Cox, 2008; Levine, 2012; MacKenzie, 2014). Likelihood is scored on a scale 1 to 3, where 1 indicates 'rare' (frequency $<<$ once in 10 years), 2 indicates 'possible' (frequency ~ once in 10 years) and 3 indicates 'likely' (frequency ~ once per year). Impact is measured on a scale of 1 to 4. Insignificant impacts (score 1) are at the edge of normal or accepted operation; minor impacts (score 2) involve recoverable short-term loss of activity or function; moderate impacts (score 3) involve recoverable but sustained delay, loss or change in function; major impacts (score 4) cause irrecoverable change or loss of function or enforced cessation of activity such



Cause of Risk	Category	Stage 1				Stages 2 to 3				Stages 4 to 6				Total	Rank
		Scale	L	I	R	Scale	L	I	R	Scale	L	I	R		
Lack of public subsidy	Innovation	Meso	2	3	6	Meso	2	3	6	Meso	2	3	6	18	1
Changing policy or regulatory framework	Political	Meso	2	2	4	Meso	2	2	4	Meso	3	3	9	17	2
Optimism bias	Innovation	Meso	3	1	3	Meso	3	1	3	Meso	3	3	9	15	3
Lack of a well-functioning market	Economic	Meso	2	1	2	Meso	2	3	6	Meso	3	2	6	14	4
Lack of access to capital	Economic	Meso	3	1	3	Meso	2	2	4	Micro	2	3	6	13	5
Significant public concern	Political	Meso	2	1	2	Meso	2	3	6	Meso	2	2	4	12	6
Operational failure	Technical	Micro	1	1	1	Micro	2	1	2	Micro	2	4	8	11	7
Lack of vocational training of the local workforce	Skills	Meso	1	1	1	Meso	2	2	4	Meso	3	2	6	11	
Quality of fuel source	Environmental	Micro	3	3	9				0				0	9	9
Insufficient capacity to construct sites	Manufacturing				0	Micro	3	3	9				0	9	
Lack of specialists in the local workforce	Skills	Meso	1	1	1	Meso	2	2	4	Meso	2	2	4	9	
Weak technology transfer environment	Innovation				0	Meso	2	2	4	Meso	2	2	4	8	12
Insufficient rate of improvement in, or lack of enforcement of, standards and codes	Political				0	Meso	1	1	1	Meso	3	2	6	7	13
Only marginal improvements likely	Innovation	Meso	1	1	1	Meso	1	2	2	Meso	2	1	2	5	14
Price volatility	Economic	Meso	1	1	1	Meso	1	1	1	Meso	2	1	2	4	15
Lack of critical materials availability	Environmental				0	Macro	2	1	2	Macro	2	1	2	4	
Lack of material substitutability	Innovation				0	Macro	2	1	2	Macro	2	1	2	4	
Unable to neutralize waste at decommissioning	Technical				0	Micro	2	1	2	Micro	2	1	2	4	
Insufficient capacity to manufacture system components or conversion devices	Manufacturing				0	Macro	1	1	1	Meso	1	2	2	3	19
Uncertain decommissioning costs	Economic				0	Micro	1	1	1	Micro	1	2	2	3	
R&D capacity or capability does not match the challenge	Innovation	Meso	1	1	1	Meso	1	1	1				0	2	21
Lack of basic education levels in the local workforce	Skills				0	Meso	1	1	1	Meso	1	1	1	2	
Infrastructure failure	Technical				0	Micro	1	1	1	Meso	1	1	1	2	
Denial of permission to access sites	Political	Micro	2	1	2				0				0	2	
Lack of social stability	Political	Meso	1	2	2				0				0	2	
Poor institutional governance	Political	Meso	1	2	2				0				0	2	
Insufficient rate of infrastructure construction	Manufacturing				0				0	Meso	1	1	1	1	27
Pollution event	Technical				0				0	Micro	1	1	1	1	
Specialist equipment unavailable	Technical	Micro	1	1	1				0				0	1	
Difficult physical access	Environmental				0				0				0	0	30
Disputed land rights or resource ownership	Political				0				0				0	0	
Lack of water availability	Environmental				0				0				0	0	
Natural hazards	Environmental				0				0				0	0	
Unable to agree a price for licence or permits	Economic				0				0				0	0	

Fig. 1 Ranked list of the scores for the causes of risk for the relevant stages (Table 1). Entries in grey are not relevant at that stage. Source: Axon, (2019)

as complete loss of fuel source, loss of life, closure of business/site/operation. This scoring of impacts takes account of the resilience of the energy system to recover or adapt following a risk event.

The likelihood and impact scores are determined for each risk in the context of the activity at each stage for each fuel. For a particular fuel the same risk may occur at different stages, but if it relates to a different activity, it must be counted each time. This is not double counting. Some of the evidence which supports the expert assessment of likelihood and impact is cited here, together with the UK case study results for the different DR supply chain stages. The literature consulted includes a wide range of published data relating to the UK, a meta-analysis of energy system performance in which risk is seldom articulated directly.

The risk score can vary between 1 and 12, with three consequence levels. Low risk scores (1–2) denote risks which are routinely managed. Moderate risk scores (3–6) require responses ranging from a 'watching brief' to some technical or policy intervention, for example. High risk scores (> 6) must be addressed—mitigation plans must be in place and/or immediate attention is needed to reduce risk level. We find in practice that our scale of risk severity (1–12) enables sufficient granularity in the analysis to locate and quantify the risks in fuel supply chains. The more nuanced distinction between risks that would be possible using a scale with more points is not justified by the quality of the data on which our risk assessments are based (Axon & Darton, 2021b). Scoring the individual risks all on the same scale avoids the need for the later introduction of arbitrary weighting factors which arise, for example, when different types of risk (economic, environmental, etc.) are rated on different scales.

In the description of each identified risk an additional element is its scale. Risks are designated as 'micro' if they relate to single sites or projects; 'meso' risks occur at the scale of the system boundary; 'macro' risks relate to widespread activity outside the system boundary. When considering the consequence for energy security of the complete risk profile of a fuel supply chain, appreciating which parts are influenced by actors at different scales helps to inform the choice of appropriate responses and intervention (Axon & Darton, 2021b).

Statistical analysis of the results for the UK case study demonstrated no systematic bias, and low sensitivity to the likelihood and impact scores for individual risks. An expert verification workshop suggested general agreement with the approach; the need for greater stakeholder consultation on the nature of risks in fuel supply chains was emphasised (Axon & Darton, 2021b).

Results and discussion

We use the academic and grey literature, particularly that focussed on the UK, to identify risks from descriptions of 'barriers', 'issues', 'difficulties', 'failures', and related synonyms. The complete risk assessment is given in Fig. 1, in the form of a ranking of total risk score for particular causes of risk for the three combined stages of DR (Table 1). The ranking of the causes of risk (Fig. 1) is indicative only and not meant to be used in isolation. The exact placement of an individual cause of risk is of secondary importance. The detail for each risk at each stage gives the richness required to develop a strategy for intervention; the distribution of the high- and medium-level risks signals where attention should be paid. We discuss the interpretation of the causes of risk in the context of a negafuel and the underlying evidence for assigning the likelihood and impact scores. For brevity we have only discussed the moderate- (yellow) and high-level (pink) risks.

Stage 1: measuring the potential

Although some companies are creating products and services, measuring the potential, for the most part, is at the research stage in the UK.

Stage 1: one high-level risk

The sole high-level risk for stage 1 is the *quality of fuel source*. In the context of DR, the risk posed is the combination of the variability of savings gained in trials and the estimated maximum potential savings. Strictly the latter is abundance or resource availability (of negafuel). Pragmatically it is not helpful to distinguish between variability and the estimated maximum because of the high uncertainty in such estimates (van den Brom et al., 2019). From the individual studies (modelling and trials) described below, we suggest that the 'quality of the fuel' as a cause of risk is in the highest category—the risk is likely to occur, and the variability may give rise to major delays in exploiting this 'resource', i.e. designing and implementing effective DR programmes. The discussion of the quality of the fuel source addresses four applications: residential dwellings, commercial buildings, industrial processes, and transport.

Despite claims for the potential of residential energy saving, Buchanan et al., (2015) observe that there is little evidence that feedback via in-home displays reduces demand. There is some evidence that installing residential PV may also reduce demand by raising awareness of energy use and cost (Keirstead, 2007). A field study by Wyatt, (2013) suggested that installing a condensing boiler and cavity-wall insulation simultaneously might yield a reduction in gas use of 14–20%, but only 8–12% when the boiler was in combination with loft insulation. The quantity of hot water use (Allen et al., 2010) and heat use (Brook Lyndhurst, 2012) vary between similar households. The patterns of use of heating vary substantially (Huebner et al., 2013a, b, 2015; Kane et al., 2015), in part, explained by a wide range of system set-point temperatures (Jones et al., 2016). Experiments using zoning of dwellings suggested a potential saving of approximately 12% of energy for space heating (Beizaee et al., 2015). The gap between projected and actual energy savings for residential thermal renovations has been quantified (van den Brom et al., 2019). Usually the magnitude of DR estimated is what could be described as the 'peak' value. Batey & Mourik, (2016) show the difficulty in retaining the levels of reductions post-study, indicating that the quality of the fuel source (i.e. negafuel) can degrade quickly with time.

Commercial buildings have received less attention. Using US data, modelling (Sun et al., 2016) estimates that the energy demand for cooling, lighting, space heating, and water heating could be reduced by 15%, 5%, 16%, and 20%, respectively, by 2035. Estimates for the UK suggest that a total saving of 70 $MtCO_2$ could be made by 2050 (LCICG, 2016b).

For industry, modelling suggests that by 2050 it may be possible to achieve reductions in total energy usage of 77% (Fais et al., 2016) and 500 $MtCO_2$ in emissions (LCICG, 2012). However, a case study of a cement production facility showed that a 4% reduction was possible at that site (Summerbell et al., 2017), and better management of the HVAC system in supermarkets might yield a 4% reduction in electricity (Mylona et al., 2017). A wide range of savings has been identified throughout the entire food chain (Tassou et al., 2014). An important role is played by systematic energy auditing to identify opportunities for energy saving in industrial operations (Selim et al., 2021; Thollander et al., 2020). Meath et al., (2016) surveyed energy saving measures for SMEs, noting the motivating factors and barriers both to technological and behavioural changes, many of which can be interpreted in terms of risks which hamper DR programmes.

Now we consider *quality of fuel source* (DR) in transport systems. Between 2002 and 2019 the number of trips shorter than one mile made by motorised transport increased by about 5%, and in 2016 the proportion of trips between 1 and 2 miles made by private motorised transport was about 60% (DfT, 2018). Also using modelling, Lovelace et al., (2011) examined energy savings from a range of scenarios by which short trips could be switched from car to bicycle, and Anable et al., (2012) suggest that the distance travelled could be reduced by 74% by 2050. The seemingly misaligned theoretical savings and field measurements suggest that the *quality of the fuel* as a cause of risk has been underestimated. Haq & Weiss, (2018) point to the wide range of uncertainties facing consumers and businesses when making transport purchasing decisions, that might make more energy-expensive options nevertheless more attractive. Reducing the energy used for shipping is an under-researched topic. However, the trade-off between speed and patterns of demand for goods and services shows that deep decarbonisation of maritime transport can only come about by a fleet-wide speed reduction (Walsh et al., 2017). Energy-saving techniques are available, both for ships at sea and for port-to-ship interactions (Hoang et al., 2022).

Stage 1: four moderate-level risks

One problem identified is the lack of continuity of funding for public programmes (De Laurentis et al., 2017), interpreted as *lack of access to capital* (economic). For energy efficiency products and services, however, Stiehler & Gantori, (2016) report that the market may grow by 7–8% p.a. One example of this potential is the comparatively poor U-values of the UK's housing stock (Guertler, 2016). On balance, we judge the *lack of access to capital* to be a moderate risk.

Turning to the causes of risk in the innovation category, Hannon & Skea, (2014) make a compelling case for the necessity of public support for basic research which assesses the possibilities and scale for DR. The *lack of public subsidy* may occur, and without public funding many programmes would suffer significant disruption; therefore, we judge this to be a moderate risk.

In the political category, we consider that the risk of a *changing policy and regulatory framework* may occur and will have a short-term effect at this stage; Ó Broin et al., (2015) suggest that further policy interventions will be required as price signals will not be sufficient to achieve DR. *Significant public concern* may arise (Brook Lyndhurst, 2012), though currently it may be more accurately described as resistance to change. Gill et al., (2011) conclude that residents need 'recalibrating' as to what 'high' and 'low' mean in terms of energy use.

Stages 2–3: creating devices, services and communication campaigns

Stages 2–3: one high-level risk

The sole high-level risk for stages 2–3 is *insufficient capacity to construct sites*. We interpret this cause of risk as uncertainty regarding the replacement rate of the housing stock with new buildings of the highest energy efficiency rating, and the rate of retrofitting efficiency measures to existing stock. Our assessment places it in the highest risk category. The rate of improvement in energy efficiency of dwellings is not only related to the rate of building and retrofitting at the best current standards but also the rate of demolition of inefficient stock (Boardman, 2007a). This lack of capacity in the construction of housing has been prevalent for a significant period in the UK (Boardman, 2007b; Boardman et al., 2005). Planning also plays a role in the insufficient rate of housing construction (Boardman, 2007a; Forde et al., 2021; Heffernan et al., 2015) and industrial facilities (LCICG, 2012). Killip et al., (2020) point to the complexity of the construction industry supply chain with its many actors, serious pressure on costs, and (often) poor quality control. These make it difficult to frame and implement policy for effective promotion of energy-saving building performance in the UK.

Stages 2–3: nine moderate-level risks

The services to deliver behaviour change are not part of a well-functioning market (economic) because the understanding is at the research stage. Some energy efficiency products are in a mature market, but the design for low carbon homes and some products are not (Heffernan et al., 2015). Overall, we consider the *lack of a well-functioning market* to be a moderate-level risk, but the impact could be significant if the effects of behaviour change programmes are not sustained or not scalable. Macroeconomic modelling (Figus et al., 2018) suggests that reductions in fossil fuel use for private transport will not be achieved through technical efficiency improvements, but probably require either travel mode switching or wholesale substitution of fossil fuel by renewables.

Killip et al., (2018, 2020) observe technology transfer issues for low carbon in the construction industry, specifically for supply chains, designers, and installers. They suggest that these are overlooked at the policy level so there is no driving force sufficiently strong to promote change. There is strong evidence of the significant scope for innovation in, for example, the steel sector (Garvey et al., 2022), new and renovated domestic buildings (Killip et al., 2014; LCICG, 2016a), non-domestic buildings (LCICG, 2016b), energy efficiency policy (POST, 2017), and demand management technologies for industry (Dyer et al., 2008). Despite this open R&D landscape, Gupta & Gregg, (2012) claim that public subsidy in housing research is essential, i.e. a *lack of public subsidy* is a significant cause of risk for future development. Likewise, the UK's energy efficiency demonstrator scheme was responsible for 25% total industrial DR between 1979 and 1989 (Griffin et al., 2012). The need for 'clean' innovation to lead long-term sustainable (i.e. zero-carbon) growth has been emphasised, together with coordinated policies and institutions to foster it (Stern & Valero, 2021); their lack constitutes an innovation risk.

In considering the political category of risks, there is some overlap with stages 4–6, but this section concentrates on the design of measures and programmes and less on the results of market-led products and services. Rosenow & Eyre, (2013) note that "*…UK energy efficiency policy is very fluid…*" and this remains true currently including for road vehicles. The importance of policy on pricing and taxation instruments is emphasised by Brand et al., (2013) who conclude that policy design should concentrate on incentive schemes with strong signals to prioritise low carbon systems. In a thorough review of European community-based behaviour change initiatives (Axon et al., 2018), it was observed that communications are the focus of most programmes with little emphasis on the role of fiscal support or regulation and legislation. Modelling work (Figus et al., 2017) suggests that it is hard to meet all targets and expected outcomes simultaneously, but nevertheless Dato, (2018) makes the case that *not* combining policy for energy efficiency and renewable energy presents a risk. The risk of *public concern* of energy technologies and services aimed at achieving DR has already occurred, for example in smart metering (Buchanan et al., 2016) and dynamic tariffs (Darby & Pisica, 2013). Another example is that of the Kirklees warm zone scheme where even though the interventions were free, there was less than 100% take-up (Long et al., 2015) with the main concern being the physical disruption to the home. When questioned about the possibility of adopting heat network members of the public liked the idea that someone else would be responsible for the maintenance but disliked the necessarily long contracts and the level of disruption.

Within the technical risk category, we can define the rebound effect as a failure of policy design and operation. Using a combination of modelling tools, Chitnis et al., (2013) suggest that a shift to a low carbon energy system will lead to an increased rebound effect. A small field study (Jones et al., 2016) demonstrated a rebound effect of space heating in social housing. The concept of the ‘prosumer’ (producer–consumer) is widely considered positive for the take-up of microgeneration; however, questions remain whether this is just a technical fix which could be considered in opposition to DR (Ellsworth-Krebs & Reid, 2016).

Stages 4–6: operating devices (electrical, heat, vehicles) or social practices

Stages 4–5: three high-level risks

The three high-level risks are *optimism bias* arising in the innovation category, *changing policy and regulatory framework* occurring in the political category, and *operational failure* in the technical category.

So-called ‘smart homes’ have long been touted as a way to reduce energy consumption, but Darby, (2018) suggests that this will simply lead to increased parasitic loads and that smart homes have little to do with energy efficiency or DR. Estimates or projections of energy savings carry uncertainty, for example retrofitting of various solutions for dwellings (Loucari et al., 2016), Passivhaus standards (Johnston & Siddall, 2016), the fabric performance of new-build dwellings (Johnston et al., 2015), heating controls (Shipworth, 2011), and the performance of non-domestic buildings (Pritchard & Kelly, 2017). Batey & Mourik, (2016) consider the performance explicitly to be a risk. In the light of the wide range of systems and situations where *optimism bias* manifests, we judge this to be a risk in the highest category with an impact that could lead to significant delays in energy efficiency improvements and DR.

The widely recognised *changing policy and regulatory framework* in the UK is acknowledged to extend to energy efficiency and DR in industry (LCICG, 2012). An important, but subtle, observation is that UK energy policy is in conflict with the aims of DR (Sun et al., 2016). UK policy is supply-side dominated, the CO_2 target incentivising fuel-switching and more renewable generation. Unstable policy and legislation (including unclear definitions) is hampering the development of the ESCO market (energy efficiency projects financed by savings) (Bertoldi & Boza-Kiss, 2017), while O’Keeffe et al., (2016) observe discontinuities in policy and its objectives. O’Keeffe et al. focus on the UK Government’s Green Deal scheme, noting that SMEs express concern about the Government’s commitment to the programme and the lack of a visible coordinating body. The lack of long-term monitoring of projects (Santangelo & Tondelli, 2017) can be viewed as not only a problem about measuring the potential for DR but also a failure of regulation particularly as public subsidies invariably support the projects.

The main risk in the technical category is that of *operational failure* of various types: some are engineering failures, others are policy or behaviour ‘failure’. Many authors identify the split incentive problem which we class as a policy failure since it is not clear where the responsibility lies between the parties, and no policy framework exists to guide or instruct them. An example is the case of the landlord-tenant relationship in a multi-occupancy commercial buildings (Axon et al., 2012; LCICG, 2016b; Scrase, 2001). It is the landlord only who can improve the energy efficiency of the building, but it is the tenant who pays the energy bills (without the control over the building environment). The problem is similar in the private rented sector (Hamilton et al., 2014; Hope & Booth, 2014; LCICG, 2016a; Reid et al., 2015), with Dato, (2018) investigating household investment in renewable energy systems specifically. A variant of the split incentive problem arises in deep retrofit projects in mixed tenure tower blocks (Bright et al., 2018) where the question arises whether the private co-owners should have to pay the bill for improvements that can only be justified as wider community benefits.

We also class the performance gap as an *operational failure*. It is well documented and refers to either optimism in the modelled or anticipated performance (Marshall et al., 2017) or lower actual performance due to installation or operation issues (Dowson et al., 2012; Johnston et al., 2016; Watson, 2015), for example. An important observation is that there is no legal requirement to fix any performance gap in the finished building (LCICG, 2016a). Operational issues of a building can be due to human factors (a ‘behavioural failure’), but other examples are data visualisation for industrial processes (Challis et al., 2017) and installers making engineering errors due the heterogeneity of installations (Fylan et al., 2016). Another common failure is retrofitting of low U-value cladding leading to over-heating (Baborska-Narozny & Grudzinska, 2017). The rebound effect (Chitnis & Sorrell, 2015) is also considered an operational failure in the context of DR, with Baborska-Narozny et al., (2016) showing that the marketing of PV systems as 'free green electricity' undermined DR, creating an unintended rebound. Turning briefly to transport, the provision of well-used cycle routes and increases in active travel did not lead to reductions in transport CO_2 emissions in the UK (Brand et al., 2014). Furthermore, the passenger vehicle rebound effect (general) is estimated as 26% (Stapleton et al., 2017). As this cause of risk has occurred and has the capacity to halt projects (particularly the split incentive problem), we place *operational failure* in the highest category.

Stages 4–6: eight moderate-level risks

There is evidence of a *lack of well-functioning markets* (economic). For improving energy efficiency the ownership and operations of networks are problematic and particularly noticeable in the UK smart meter roll-out programme (Pyrko & Darby, 2011). The energy service company market is noted as having high transaction costs which inhibit market entry (Bertoldi & Boza-Kiss, 2017). Two other indicators of a weak market structure are "*green over-pricing*" observed by Heffernan et al., (2015) and low energy price elasticity (Eyre, 2013). The *lack of access to capital* (economic) is described by various authors (Brown & Chapman, 2021; POST, 2017; Rosenow & Eyre, 2013). According to Booth & Choudhary, (2013) risk arises because the benefits are not all measured in the reduction of consumer energy bills, but financially unquantifiable improvements such as thermal comfort or health. They claim that only loft insulation and draught excluders show a net present value greater than zero. In the residential housing sector there are specific issues for private landlords (Reid et al., 2015), social landlords (Liu, 2018), adopting zero-carbon technologies (Caird et al., 2008), and renewable energy systems specifically (Dato, 2018). Dato, (2018) also makes the case that poorer households need additional financial support, even for energy efficiency measures. In the previous stage we noted that the expected payback periods in industry for energy efficiency measures might scupper projects, but even if they go ahead access to capital may still be a barrier (LCICG, 2012). In commercial buildings the trend towards shorter leases reduces the tenant's appetite for DR unless payback time of any project is similarly short (Elliott et al., 2015).

Turning to the innovation category, although some areas of energy efficiency are mature, others—including retrofitable technologies (Gooding & Gul, 2017)—have plenty of scope. The energy efficiency of homes and businesses is in part about the interaction of technical innovations and the willingness of people to adopt them and adapt their behaviours. This led Shove, (1998) to question whether people really do have technologies "*transferred upon them*". This somewhat reductionist process assumes that the uptake of energy efficient technologies (for buildings) simply requires overcoming non-technical barriers; but this may well be missing the point, and perhaps explains the hit-and-miss nature of the take-up of devices and practices. We assess this to be an underestimated cause of risk. The cost of financing R&D is widely accepted as requiring public support, but because of the high absolute costs early adopters of industry energy efficiency measures may also need subsidies (LCICG, 2012). Analysis of patents (Bonilla et al., 2014) shows the importance of public R&D (in addition to oil price) for innovation in diesel engines.

In the political category, the *development and enforcement of codes and standards* are a recognised risk in several areas of residential (LCICG, 2016a) and commercial buildings (LCICG, 2016b). Two examples are the current building regulations (Heffernan et al., 2015) and the installation of zero carbon technologies (Caird et al., 2008). The lack of standardisation is put forward by Fawkes, (2015) as a deterrent to investment. In the context of DR, *significant public concern* manifests as lack of engagement or willingness to make changes, e.g. due to added complexity (Parrish et al., 2020). An important tool available to the government is taxation and although it could be effective at driving policy for DR, it is deeply disliked by the citizenry (Eyre, 2013). Homeowners exhibit scepticism about the effectiveness of some new technologies (Ipsos, 2013) and will not undertake even the easiest efficiency measures (Palmer et al., 2012). The latter may be due to the low level of importance they place on energy, or the dislike of the disruption and hence inconvenience caused (Rosenow & Eyre, 2013). There may also be aesthetic reasons (Sunikka-Blank & Galvin, 2016) or cultural factors (Dowson et al., 2012; Hards, 2013; Heffernan et al., 2015; Olaniyan & Evans, 2014). Despite a plethora of evidence for public concern, we also note that the UK economy's energy intensity per job has been falling steadily since at least 1990 (Roberts et al., 2019), as has the thermal demand per unit output (Roberts et al., 2015). This tension between home and work might be summed up as a lot of fuss by a public that mistrusts change, whereas the workforce quietly adopts new technologies and practices. Buyers of new-build homes are concerned about the quality of work delivered, but loss of reputation for housebuilders appears not to be a sufficiently strong incentive to improve the quality of work.

Skills—a cross-cutting issue

The *lack of appropriate vocational and specialist skills* in the UK workforce is judged to pose a moderate level risk arising at stages 2–3 and 4–6. In the industrial sector there is a lack of energy management professionals, with the food and drink industry considered critical (LCICG, 2012). For commercial buildings, the installation, commissioning, and operation of building services have been identified as suffering a skills shortage (LCICG, 2016b; Engineering UK, 2018). In the residential sector, it is recognised that designers lack knowledge to create dwellings to passive house and zero-carbon standards (respectively) (Heffernan et al., 2015; Pitts, 2017) that specifying and estimating skills are a problem (Glass et al., 2008), and that technical skills for retrofit are lacking (Fylan et al., 2016; Gooding & Gul, 2017; Killip, 2013; LCICG, 2016a). According to Fylan et al. (2016) installers lack the knowledge of the technologies and products to make good adaptations, which is less of a problem in high-volume new-build. There is also some evidence of a lack of facilitators in the ESCO market (Bertoldi & Boza-Kiss, 2017). There is evidence that building regulations are not strictly followed (Boardman, 2007a; Killip et al., 2020) which may in part be due to the standard of construction skills in the UK.

The relative position of DR compared with other fuels

Table 2 The absolute scores for DR at each stage. The normalised risk score is only generated at the final step to minimise rounding errors. The risk score is calculated from Fig. 1

Stage	Risk score (abs) DR	Average non-renewables [a]	Average (all fuels) [b]
1	42	52	37
2–3	67	140	118
4–6	86	108	70

[a] Source: Axon, (2019)

[b] Source: Axon & Darton, (2021a)

Table 2 presents the risk scores for DR at each stage and the comparison with other non-renewables and the average for all fuels. We observe for stage 1 that although the risk score for DR is lower than the average for other non-renewables, it is higher than the average for all fuels. Stage 1 is measuring the potential of DR as a resource (negafuel) and its relative score reflects the need for less investment to explore for negafuel resource compared with fossil fuels, but acknowledges that investigating DR is a process more complex than measuring the potential of most renewables. Similarly, the risk associated with stages 2–3 for DR is significantly lower than the average for both other non-renewables and the average for all fuels. At stages 4–6 (convert, distribute, use) DR risk is again lower than the average for other non-renewables, but higher than the average for all fuels. This reflects the relatively poor levels of maturity of DR compared with all fuels.

The full list of risk scores for all fuels, not examined in detail here, is given in the Appendix. As expected, non-renewables cluster mainly at the top while renewables cluster at the bottom. Overall DR has a normalised risk score of 45, placing it mid-way between the most and least risky fuels. At first glance this is a surprising result for what is termed the 'first fuel'. However, our analysis assesses identified risks, not what may be intuitive, nor what may be desirable from a sustainability viewpoint (efficiency). This distinction can be thought of as between stating that efficiency *'is'* and that it *'ought to be'* the 'first fuel'.[1] In Table 3 we summarise various characteristics of DR resulting from the risk assessment method. DR is a non-renewable resource because when an action is taken to eliminate a particular (part of) demand, that exact action cannot be repeated.

The top-ranking risk (Fig. 1) is *lack of public subsidy*. Programmes to promote DR commonly rely on public funding to get started, for example to stimulate commercial activity in the early phase. Yet, the second-highest ranked risk is *changing policy or regulatory framework* which has afflicted UK policy towards DR for many years. Continuity and consistency in policy help establish fledgling industries. The

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[1] This distinction was brought to our attention by Prof. N.J. Eyre, *Pers. Comm,* September 2022.

Table 3 Summary of characteristics of DR as a negafuel

Characteristic	Result
Fuel type	Non-renewable
Risk group	Bioliquids, Demand Reduction, ocean (tidal), ocean (wave), waste
Normalised risk score	45
Relative position	11/19 most risky
High-level risks (number)	5
Moderate-level risks (number)	21
High-level risks	Quality of fuel source (stage 1), Insufficient capacity to construct sites (stages 2–3), optimism bias (stages 4–6), Changing policy or regulatory framework (stages 4–6), operational failure (stages 4–6)
Riskiest category	Innovation
Riskiest stage	Stages 4–6
Most significant source of risk	Lack of public subsidy

next highest-ranked risk is *optimism bias*, which has led to disappointment when programmes have not met their targets. This background of uncertain support and unexpected outcomes perhaps explains the next two highly ranked risks, *lack of a well-functioning market* and *lack of access to capital*. If energy is relatively cheap, which is also an objective of government policy, the value of negafuel remains low; thus, investment in DR is hampered. As a result, it is both difficult to establish a market for products and services related to DR, and to encourage the workforce to obtain the necessary vocational and specialist skills.

Conclusions

Our analysis shows that DR is far from risk-free. Moreover, the risk analysis method (in this case applied to the UK) identifies a small group of high-scoring risks that, taken together, suggest a narrative explaining why accomplishing DR is difficult. Each of the activities in the supply chain attracts risks in various forms. Our method and analysis show that the causes of these risks are not evenly distributed and have differing importance along the supply chain. Understanding the distribution of causes of risks sheds light on potential priorities for policy intervention and gives detail about the process of DR not previously considered in a single analysis. DR requires specific policy instruments to give necessary coherence to its promotion across the energy economy (all fuels); this reinforces the benefit of considering DR delivered by its own supply chain, rather than as an aspect of other fuels.

Demand Reduction appears near the middle of the risk-ranking of fuels. It seems likely that this explains why DR programmes have not achieved the impact expected—the risks involved have been underestimated previously. The misaligned theoretical savings and field measurements suggest that, in particular, the *quality of the fuel* (reliability of expected DR benefit) as a cause of risk has been underestimated. The activities associated with creating devices, services, and communication campaigns are often considered the essence of DR. However, our analysis shows that the other two stages of activity (measuring the potential and operating devices and social practice) carry greater risks though these risks are less often recognised. DR is seldom incorporated into future energy scenarios which usually focus on primary energy supply, thereby neglecting the contribution that could be made by reducing demand. We suggest that by treating DR (or energy efficiency / saving) as a 'negafuel', it can be given equal status with fuel supply.

Declaring efficiency as the 'first fuel' is clearly not having the desired effect. Our work shows that it is not the 'first fuel', since there are other actual fuels which can meet demand at lower risk: thus, it appears to be less risky to add more PV or wind capacity to the electricity network, for example. The common presumption that DR is cheaper than buying fuel is simplistic—it fails to price in the direct costs and the risk of the DR route. The implied discount rate of the future value of DR is very aggressive, meaning that the long-term value of DR is not recognised, suggesting that DR is not worth investing in at the present time.

Thinking about risk in the context of DR, rather than, say drivers and barriers suggest that risk mitigation techniques should be part of the design process for programmes of DR, whether these are public pilot programmes, policy, or commercial products. Barriers are an ill-defined entity that may not be quantified. Identifying explicit risk, on the other hand, enables pricing in the risk of an outcome not being achieved, providing a new set of tools to deploy. We propose that a holistic risk-based approach to DR—including treating it as a nega-fuel—will open-up new fronts to understand how to create programmes of DR which address the risks, and which consequently may be more successful than previous programmes.

Formulating policy and regulation to promote DR should take account of the significant risks involved. In the UK there is a need to match policy for DR to the government's long-term commitment to achieve Net Zero by 2050. DR potentially has an important role in meeting this goal, but policy is necessary to help develop and introduce the devices and social practices necessary. Policy should aim to provide appropriate subsidies, create a stable environment for DR investment, set appropriate regulations and standards, and support the provision of required skills in the workforce.

The methodology of our risk assessment is robust and transparent, and should be applicable to any energy economy, though the quantification of particular causes of risk will depend on the case considered. The UK case study benefits from a significant volume of literature and reports describing energy supply and demand in the UK, but similar evidence may not be available for other jurisdictions. It is likely that similar energy economies may exhibit similar risk profiles, though this remains to be shown by further study.

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Data availability All data generated or analysed during this study are included in this published article.

Declarations

Competing interests The authors declare no competing interests.

Appendix

Table 4 Ranked list of fuels and the number of associated high-level risks. The ranking is not weighted for the availability of each fuel. The clustering of the fuels into groups is also shown. Error analysis shows that the attribution of fuels to groups is robust (Axon & Darton, 2021a). Source: Axon, (2019) and Axon & Darton, (2021a)

Fuel	Fuel type	Normalised risk score (a.u.)	No. high-level risks	Cluster
Gas (unconventional)	Non-renewable	100	12	1
Gas	Non-renewable	99	11	
Oil	Non-renewable	98	10	
Nuclear (fission)	Non-renewable	94	17	
Thermal (geological)	Non-renewable	80	11	2
Biomass (solids)	Renewable	65	3	
Coal	Non-renewable	65	6	
Biogas	Renewable	61	2	
Bioliquids	Renewable	48	1	3
Ocean (wave)	Renewable	47	9	
Demand Reduction	**Non-renewable**	**45**	**5**	
Waste	Non-renewable	43	3	
Ocean (tidal)	Renewable	42	6	
Thermal (low temperature)	Renewable	37	4	4
Wind (offshore)	Renewable	34	4	
Wind (onshore)	Renewable	32	5	
Hydro	Renewable	31	5	
Solar (electric)	Renewable	25	3	5
Solar (thermal, water)	Renewable	20	1	

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