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The economics of flexibility service contracting in local energy markets: A review

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ABSTRACT

Electricity networks require reinforcing to accommodate increasing penetration of renewables and increasing electrification of heating and mobility. The nature of these reinforcements depends on the scale and depth of demand reductions and flexibility services available to solve constraints. Local energy markets are posited as a means to capture, aggregate, and trade flexibility services in network-constrained areas. Using insights from transaction cost economics, this review adapts a theoretical model to analyse the contractual arrangements underpinning both local energy markets and the delivery of flexibility services therein, and the end-to-end process of flexibility service delivery. By facilitating the identification, analysis, and comparison of the relative magnitude of associated transaction and production cost variables, it helps identify factors which determine their viability. This model is tested on Great Britain's Local Energy Oxfordshire project (Project LEO) which sought to establish the potential for flexibility service provision to support the transition to a renewables-based electricity system by developing a proof-of-concept local energy market. It reveals transaction costs which significantly outweigh contract revenues at this stage of market development. Standardisation and regulation lower transaction costs in the establishment of local energy markets, while automation and aggregation lower transaction costs and increase contract revenues of flexibility service delivery. Support needs to be appropriately targeted to lower these costs vis-à-vis network reinforcements, and the overall costs of transitioning to net zero.

1. Introduction

Reaching the UK's net-zero carbon emissions by 2050 requires the reduction of energy demand, the electrification of heating, transport, and industrial processes, and the decarbonisation of electricity supply by 2035 [1,2]. Scenarios developed by Great Britain's (GB) National Grid, meanwhile, foresee an increase in residential electricity demand for heating from 20 TWh in 2022 to 60-80 TWh by 2050 [3]. To accommodate this increasing demand, Ofgem, Great Britain's electricity and gas market regulator, projects that 30 GW of low carbon flexibility capacity will be required in 2030 and 60 GW in 2050, up from 10 GW in 2021 [4]. Such flexibility could reduce system costs by £30-70bn/a, mainly from lower generation capital costs through the better utilisation of generation assets [3,4].

Electricity market reform and the establishment of new standards are necessary to improve flexibility, enable the decarbonisation of electricity generation and electrification of heat and transport, and ensure affordability, reliability, compatibility, and interoperability [5–7]. While interoperability is being addressed through the establishment of regulatory requirements and the development of two standards, the Public Available Specifications 1878 and 1879 [8], electricity market reform is being considered in REMA, the Review of Electricity Market Arrangements [7]. New market arrangements could provide flexibility through changes to the charging regime and the development of local energy markets (LEMs) on one hand, or a more fundamental shift towards locational marginal pricing on the other, although there is uncertainty how these would interact with the current energy price cap [4,6,7].

This paper reviews the economics of providing flexibility services in LEMs using insights from transaction cost economics [9–16]. Flexibility services encompass temporary changes in the way electricity is

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List of abbreviations:

BEMS	Building energy management system
DNO	Distribution network operator
DSO	Distribution system operator
EDF	Energie de France
ESCO	Energy service company
ESO	Electricity system operator
GW	Gigawatt
LCH	Low Carbon Hub
LEM	Local energy market
LEO	Project Local Energy Oxfordshire
M	Marginal cost of flexibility provision into the LEM by the grid-edge contractor
NMFP	Neutral Market Facilitator Platform
OCC	Oxford City Council
P2P	peer-to-peer
P_{CL}	Production costs incurred by the DSO client
P_{CON}	Production costs incurred by the grid-edge contractor
R	Remuneration paid to grid-edge contractor for flexibility provision in the LEM
REMA	Review of Electricity Market Arrangements
SEPM	Sustain Export Peak Management
SPM	Sustain Peak Management
SSEN	Scottish and Southern Energy Networks
TC	Transaction costs
Tr_{CL}	Transaction costs incurred by the DSO client
Tr_{CON}	Transaction costs incurred by the grid-edge contractor
TSO	Transmission system operator
TWh	Terawatt hour

generated, stored or its demand managed upon request to support efficient operation and decarbonisation of the electricity network [17–25]. LEMs are geographically and time limited marketplaces where such flexibility is traded from suppliers (end users) of demand response to flexibility users such as distribution network operators (DNOs), transmission system operators (TSOs), and third parties [26–34]. Initially, analysis of flexibility service provision in LEMs focused mainly on technical challenges [35–43]. Particular emphasis has been placed on peer-to-peer (P2P) markets and trading [44–49]. Related business and policy analysis, meanwhile, has focused on acceptance [21,50], aggregation [14,15,32,41,45,51], contracting [16,37,52], procurement [23,27,33,53], market-design [25–30,54,55], governance [33,56], end-user engagement [21,25,29,57,58], tokenisation [59,60], and profitability [15,61–63].

A transaction cost perspective, however, is largely absent in these analyses with the notable exception of [16,64,65]. Such costs encompass time or inconvenience expenses associated with searching, bargaining, and opportunism which are incurred when conducting an economic transaction. As they do not accrue as benefits or value to any participant of the transaction, they are sunk costs [9–13,16]. This paper adapts a theoretical model of energy service contracting decisions developed by Sorrell [10] which uses insights from transaction cost economics to determine the viability of governance (contractual) arrangements [9–13,16,66] and to review the cause and nature of transaction costs in LEMs. Project Local Energy Oxfordshire's (LEO's) LEM is the case study. This £40m 3-year (2020–2023) LEM trial sought to establish the right balance between reinforcing the grid (network solutions), which is generally considered the most expensive and least desirable business case, and prioritising flexibility (flexibility solutions), to avoid or defer such grid reinforcements and help balance electricity both locally and nationally [67–69].

This paper is structured as follows: Section 2 provides background information on flexibility services and Project LEO. Section 3 summarises the methodology and the economics of flexibility service contracts. Section 4 reviews the system and transaction costs of procuring LEMs and flexibility service contracting therein. Section 5 discusses pathways to lower such costs and the overall economics of flexibility service contracting in LEMs. Section 6 concludes.

2. Background

2.1. Flexibility services

With the increasing diffusion of intermittent and distributed generation and the coinciding increasing demand for grid connections in GB, electricity networks must deliver increasing volumes of electricity [3,4,70]. Without significant investment, there is not enough capacity to handle increasing loads of fluctuating supply from renewable sources at transmission level while at distribution level there is not enough capacity to handle the simultaneous electrification of heating and mobility [4]. Increasingly, excess generation results in payments to generators to curtail and negative pricing when intermittent supply does not match up with demand. 2020 in GB, costs for curtailment amounted to £250m, or £4/MWh, while the wholesale price for electricity was negative for 2 % of the time [71].

Flexibility is key to turning these costs into value [19,22,52,62,63,72]. Advances in storage, smart metering, and ubiquitous internet-connected monitoring, control, and automation, as well as education and behaviour change, provide opportunities to increase flexibility by managing supply and demand from centralised provisioning down to the grid edge [3,4,6,7,17,19,23,24,27,33,67–69,73]. In GB, flexibility services in electricity networks are typically used by [74: 11].

- "The ESO [electricity system operator - TSO] in balancing the electricity system in real-time e.g., frequency services to manage the imbalance between the level of national demand and the aggregate level of generation
- The DNO [or distribution system operator – DSO] in managing the distribution network e.g., services to reduce the demand of a DER [distributed energy resource] during peak demand times to avoid additional investment in infrastructure and enabling more demand to connect
- Market actors working with each other to address their own issues e.g., trading import and export capacity between sites to enable increased generation or demand in the local area and avoiding investment in new infrastructure that would delay development
- Market actors managing their own price risk e.g., reducing demand when electricity prices are high"

For TSOs and DSOs (DNOs), flexibility services help reduce costs of operating and managing transmission and distribution networks respectively [23–27]. For market actors, which includes any organisation involved in modulating energy supply and demand, flexibility services can create revenue streams and reduce carbon emissions, although this largely hinges on aggregation to achieve economies of scale [14,15,32,41,45,51]. A study conducted as part of LEO suggests that flexibility provision in GB can reduce system costs by £4.55bn/a through savings from avoided network capacity (£2.7bn/a), reduced peaking generation capacity (£0.75bn/a), and reduced curtailment/saving on generation fuel (£1.1bn/a). Storage could increase this figure to £5bn/a [71]. In total, untapped DER flexibility potential might amount to as much as 22 GW [75]. To establish the potential contribution of flexibility to achieve such cost savings, flexibility contracting trials in proof-of-concept markets such as Project LEO's LEM are underway [67–69,76–79].

2.2. Transaction costs in flexibility service provision

The challenge of providing flexibility services has long been approached through a technical lens [35–43]. However, with the launch of LEMs in trials such as Project LEO and the completion of flexibility service contracts within, issues surrounding regulation, business models, and, above all, transaction costs have surfaced [16,54,64,65,67–69]. These build on the growing body of literature which identify transaction costs as one of the main drivers of energy market failures, especially in contract-based markets [79–93]. However, the total number of publications analysing flexibility markets through the lens of transaction costs is very limited. A Scopus search (ALL ("flexibility market*" AND "transaction costs" AND "energy")) identified 26 papers. After screening their abstracts, a detailed keyword search, and further searching on Google Scholar only 13 were identified as relevant [16,28,30,48,53,55,64,65,79–83] (see Table 1).

According to Table 1, only four of these papers refer specifically to transaction cost economics [16,64,65,79]. Only two of these papers use these insights in their analysis [16,65]. Dronne et al. [65] develop a simple numerical model to help identify an optimal market design to coordinate network and flexibility development. Mandel and Pato [16] analyse the nature of such costs alongside other market access failures which underpin the inherent bias in EU markets towards energy supply infrastructure. Both identify asymmetric information as key barriers in the emergence of flexibility markets and this paper uses insights from both these approaches. They also echo findings on the wider issue of transaction costs in energy service contracting which was first extensively analysed by Sorrell using insights form transaction cost economics [9–12,84–89].

In principle, transaction cost economics is concerned with the relative magnitude of variables in contractual arrangements as "mathematical economics captures only a fraction of the transaction-cost phenomena of interest" [9: 261]. By focusing on the legal arrangements required to enforce transfers of titles rather than the legal concept of sale, it requires "an interdisciplinary approach to the study of organisations that joins economics, organization theory, and aspects of contract law" [11: 22]. In such analysis, ex ante and ex post costs "are often difficult to quantify [which] is mitigated by the fact that transaction costs are always assessed in a comparative institutional way, in which one mode of contracting is compared with another" [11: 22]. A growing body of literature uses insights from transaction cost economics in the analysis of various aspects of the energy system transition to zero carbon, especially on the demand-side where transaction costs are among the most significant barriers [12–16,65,66,84–98].

Table 1
Comparison of existing studies taking on transaction costs in flexibility markets.

	Flexibility market	DSO procurement	Transactional cost	Transaction costs	TC Analysis
[16]	X	X		X	X
[28]					
[30]	X	X			
[48]					
[53]	X	X			
[55]	X				
[64]				X	
[65]	X	X		X	X
[79]	X			X	
[80]	X	X			
[81]		X	X		
[82]			X		
[83]		X	X		

3. Methodology

3.1. The economics of flexibility service contracts

To compare the relative magnitude of variables in flexibility service contracting, the framework developed by Sorrell [12,66,84] is modified by taking into account findings by Dronne et al. [65]. This combined approach facilitates a review of transaction costs involved in the procurement of both LEMs and the provision of flexibility services within to help identify conditions under which flexibility service contracts are likely to succeed. In principle, production and transaction costs will be incurred by the DSO for extending the grid network as well as for procuring both LEMs and flexibility services within [65]. In case of the LEM and flexibility service provision, production and transaction costs will also be incurred by the grid edge flexibility provider (contractor).

The key difference between energy service contracting and flexibility service contracting in LEMs are greater information asymmetries, the inverse governance of the client-contractor relationship, the small economic/flexibility potential available among contractors, and their limited temporality [17–27,65], which is described in greater detail below. The value proposition underlying the motivation for a DSO-client (in this case SSEN) to create a LEM and enter into flexibility service contracts with grid-edge contractors is as follows:

> "The DSO is tasked with ensuring a safe, secure and reliable network, accommodating electricity flows required for the energy transition in a cost-effective way. This includes consideration of flexibility as an alternative to infrastructure until there is a more certain future. The ceiling price for flexibility is based on the cost benefit analysis for network reinforcement with an optionality premium for the benefit of deferral until there is a more certain future. Below the ceiling price, flexibility has a positive NPV for a period and above the ceiling price, network reinforcement is a better solution" [76: 49–50]

SSEN's calculations from 2021 suggested that a flexibility first approach will allow them to defer up to £46m of reinforcements and procure 5 GW of flexibility between 2023 and 2028 [76]. A grid-edge flexibility contractor in such LEMs "is a user who provides flexibility services by making temporary changes to the way they consume, generate, or store electricity when requested" if contract revenues exceed the costs of making assets flexibility-ready, establishing all the relevant contracts and protocols, and providing flexibility services [12,16,23,65,66]. *Transaction costs* are monetary, time, or inconvenience expenses incurred by both client and contractor which can be categorised as [99–102].

- *search costs* associated with tendering, identifying a potential client or contractor, verifying their suitability, preparing and evaluating bids and selecting a preferred contracting partner;
- *bargaining costs* associated with negotiating and preparing the contract, monitoring contract performance, enforcing compliance, negotiating changes to the contract when unforeseen circumstances arise and resolving disputes; and
- *opportunism costs* associated with either party acting in bad faith [12,66].

These costs and variables are analysed by combining qualitative methods, ranging from interviews and workshops, with quantitative methods, ranging from the calculation of flexibility potentials to the analysis of temporal transaction cost savings. These were written up and made publicly available in 40 reports, including three annual reports which synthesize the findings of each year (available at https://project-leo.co.uk/reports/). Thanks to LEO's focus on data optimisation and automation, the project also produced a wealth of outputs covering aspects of LEM creation and flexibility service provision ranging from the capability of market actors to measurement and verification protocols.

Of particular interest for this paper were findings regarding the contractual arrangements which enable LEMs and flexibility service provision and associated transactions and the analysis of temporal transaction cost savings. The former are mainly derived from four annual rounds of interviews, each following a simple topic guide, with a total of 52 interviews which were transcribed and coded using NVivo. The latter are derived from calculations provide by community flexibility provider and aggregator Low Carbon Hub (LCH), which are complemented with data from Oxford City Council (OCC). To identify these and other transaction cost savings discussed in detail in Section 4, follow-up meetings with several LEO project representatives were held in the final months of the project (January–March 2023). The following section provides the rationale for reviewing the provision of flexibility services through a modified framework for analysing energy service contracts.

3.2. The governance of flexibility service contracts

In principle, the establishment of an LEM for flexibility service contracting is akin to an energy service contract [12,66,88,93,103]. However, there are some key differences which determine the framework presented in the following sections. While energy service contracts involve "outsourcing of one or more energy-related activities at a site or group of sites under the terms and conditions of a long-term contract" to the ESCO [66: 421], flexibility service contracts in LEMs outsource the responsibility for cost savings to end use contractors. This is achieved by "making temporary changes in the way you consume, generate or store electricity when requested, to support a more efficient use of the energy network" [104]. As a result, the contractor-client relationship is nearly inverse: While the specialised DSO client owns or manages the infrastructure, the end user (in this case the 'contractor') typically owns or manages centralised and decentralised assets and controls useful energy or work streams which DSO clients seeks to adjust to save *cost*.

The governance of transactions among client and contractor in both cases refers to the design of contractual arrangements with regards to contract duration and allocation of responsibilities, and associated risk and complexity, especially at the procurement stage [12,66,89,94,95]. In the context of flexibility contracts, as with energy service contracts, it is useful to conceptualise modes of governance as a range between hierarchies and markets (Table 2) [94,95].

Flexibility service contracting in LEMs, unlike energy service contracting, involves two modes of governance. The first concerns the governance of the LEM. As artificial constructs, LEMs are procured by DSO clients using relational contracts ideally with a range of contractors capable of delivering both DSO-procured and DSO-facilitated flexibility services (centre of Table 2). Such services (ranging from Sustain Peak Management to Maximum Export Capacity; see Annex 1), in turn are transacted within the confines of the artificial LEM using short-term (month-ahead), simplified short-term (week-ahead), and sport-market (day-ahead) contracts (bottom right of Table 2) either directly with the Neutral Market Facilitation Platform (NMFP) or indirectly via a third party flexibility market platform provider (section 2.2) [67–69].

This two-stage process is similar to the process of establishing procurement frameworks for energy service contracting [66]. In these cases, the procurement (aggregation) of multiple contractors to establish such frameworks lowers the task complexity of procuring individual energy service contracts while increasing competition, thereby lowering *transaction costs* of the entire contracting process (see Table 2) [14,15,32,41,45,51,66]. To sum up, in energy service contracting, a con- or prosumer (client) procures such services from a market actor (contractor) *outwards towards* the grid-edge typically involving a single stage governance process using long-term contracts (see Table 2). In flexibility service contracting in LEMs, a market actor (client i.e., the DSO) procures such services *inwards from* end-use consumers and prosumers (contractors) involving a two-stage governance process involving both relational and short-term contracts (see Table 2).

3.3. Framework to review the cost and revenues of flexibility service contracts

For the DSO client, increasing electrification and penetration of renewables lead to *network constraints* which can be addressed through grid reinforcement or the procurement of flexibility services. The viability of flexibility service contracting hinges on the following conditions [12,65,89]:

Superscript *Grid* refers to in-house grid investment of the DSO client, the superscript *LEM* to in-house LEM investment of the DSO client and the grid-edge contractor, and the superscript *Flex* to outsourced flexibility provided by the grid-edge contractor.

The first condition for a viable LEM is that the total cost by the DSO client of establishing (producing) the LEM and remunerating flexibility within are less than the cost of grid reinforcement, including associated transaction costs.

$$\left(P_{CL}^{Grid} + Tr_{CL}^{Grid}\right) > \left(P_{CL}^{LEM} + R^{Flex}\right) + \left(Tr_{CL}^{LEM} + Tr_{CL}^{Flex}\right)$$

The second condition for a viable LEM is that the total flexibility remuneration that the grid edge contractor can expect to receive over time is greater than the total cost of providing (producing) flexibility capability to establish the LEM and the marginal cost of providing flexibility itself within, including associated transaction costs.

$$R^{Flex} > \left(P_{CON}^{LEM} + M_{CON}^{Flex}\right) + \left(Tr_{CON}^{LEM} + Tr_{CON}^{Flex}\right)$$

This paper focuses on this second condition as Project LEO sought to establish the viability of flexibility service contracting in an LEM. The third condition is that the total saving in production costs of establishing the LEM, and of procuring, providing and remunerating flexibility within relative to the production cost of grid reinforcements, must be greater than the total increase in transaction cost.

$$\left(P_{CL}^{Grid} - \left(P_{CL}^{LEM} + R_{CL}^{Flex}\right)\right) - \left(\left(Tr_{CL}^{LEM} + Tr_{CL}^{Flex}\right) - Tr_{CL}^{Grid}\right) \geq \left(P_{CON}^{LEM} + M_{CON}^{Flex}\right)\right) + \left(Tr_{CON}^{LEM} + Tr_{CON}^{Flex}\right)$$

The relative magnitude of the following six transaction attributes is

Table 2
The governance energy service and flexibility service contracts (adapted from Ref. [90]).

Governance	Hierarchies …					Markets …
Contracts	Vertical Integration	Relational contracts	Long-term contacts	Short-term contracts	Simplified short-term contracts	Spot market
Energy service contracts	In-house management of energy services	Municipal Utility Company	Energy Service Company	Energy Utility Company	Energy service arrangement for an event	n/a
Procuring Local Energy Markets	Automated network management OR network reinforcement	Organisations with low and medium voltage level assets	Institutional high-voltage level flexibility providers	n/a	n/a	n/a
Procuring flexibility contracts	Automated network management OR network reinforcement	n/a	n/a	Month-ahead contracts	Week-ahead contracts	Day-ahead contracts

sufficient to indicate the most efficient governance strategy: *asset specificity* (site, physical, human-capital, dedicated, and intangible), *task complexity* (information asymmetry – high complexity encourages vertical integration), *economic potential* (flexibility potential of assets), *frequency* (higher frequency in this case refers to the anticipation of recurring spot-market demand for flexibility), *competitiveness* (when flexibility potential is distributed across many sites and clients) and *aggregation* (when such sites and clients can be aggregated in single contracts) [9–16,65,89].

To avail of *flexibility remuneration*, end-use contractors need to adjust energy generation, conversion, distribution, and control equipment to avail of flexibility potential. Such adjustments are associated with staff and material costs of equipment preparation, response, and maintenance, which are a function of the suitability of such assets for flexibility service provision (*asset specificity*). Contracting is more viable for generic technologies and processes with low *asset specificity* such as boilers, chillers, and lighting systems, when the *economic potential* of flexibility provision is large and widely distributed (Fig. 1; [12,65,89]).

Transaction costs are determined by the *economic potential* of assets capable of providing flexibility vis-à-vis grid reinforcement costs; *asset specificity* and changes to routines and technologies to provide flexibility vis-à-vis normal operating conditions; *task complexity* associated with both the contractual establishment of LEMs and the end-to-end process of delivering flexibility; the *frequency* of flexibility transaction; the potential for *aggregation*; and market *competition* (Fig. 1; [12,65,89]).

Contracting may be less viable if physical and human assets are highly specific to a particular process and cannot be easily adjusted (*asset specificity*), when tasks to adjust processes and technologies associated with the end-to-end process are complex and time-consuming (*task complexity*), and there are few flexibility assets available which lower *competition*, and demand for flexibility is uncertain (*frequency*). *Aggregation* can lower transaction costs if third-party intermediaries negotiate multi-site contracts and manage the end-to-end process while *frequency* can see remuneration exceed increasing transaction costs of frequent flexibility service provision (Fig. 1; [12,65,89]).

Given the proof-of-concept stage of LEMs, flexibility service contracting is associated with significant *task complexity* associated with both establishing LEMs and the end-to-end process of responding to a flexibility request (Fig. 1). Associated *search costs*, *bargaining costs*, and *opportunism costs* can be broken down as follows (Table 3).

Given the two-stage process, there is a wide range of *transaction costs* involved in flexibility service contracting (Fig. 1 and Table 3). However, as LEMs such as Project LEO are in their proof-of-concept stage as opposed to mature markets, there are ample opportunities to lower these costs relative to *remuneration*.

3.4. Project LEO

Project LEO is a suitable case study as a result of grid capacity issues and ambitious carbon emission reduction targets associated with electrification of heating and mobility and increasing penetration of intermittent generation in Oxfordshire. To address these issues, DSO SSEN developed a proof-of-concept LEM interoperable with existing infrastructure [67–69]. The primary output was specified as follows [67]:

> "A smarter energy system will provide new opportunities for communities to engage and for low carbon technologies to compete with solutions in an open and fair market. LEO is testing how we turn the aspiration of a system that supports community engagement into a reality"

LEO sought to pave the way for a smart, fair, and renewables-based energy system for almost 700,000 people while maintaining services within the legacy network through its proof-of-concept LEM procured by SSEN as part of LEO [67–69]. As entirely artificial constructs, the depth, scope, and duration of LEMs is determined by the DSO, in this case SSEN. LEO's LEM trials adapted the basic structure outlined in Fig. 2a (see also Annex 1).

This structure enables interaction with third parties, technology platforms/service providers, and flexibility asset owners (Fig. 2b) involved in flexibility service provision with different degrees of separation. As bilateral coordination between these different stakeholders would be too costly, SSEN established the Neutral Market Facilitator Platform (NMFP; Fig. 2c) to facilitate transactions [34]. The NMFP is an IT platform built specifically for the LEM by SSEN. Establishing such markets requires contracting arrangements between the DSO on one hand and intermediary technology platforms, flexibility asset owners, and third parties (more on this below) on the other hand (depicted as blue lines in Fig. 2b). Once contracts are in place and flexibility capabilities established, flexibility services are procured by the DSO via auction on the NMFP among intermediary technology platforms and service providers (depicted as red lines in 2c). These intermediaries, in turn, send a request to flexibility asset owners who provide flexibility

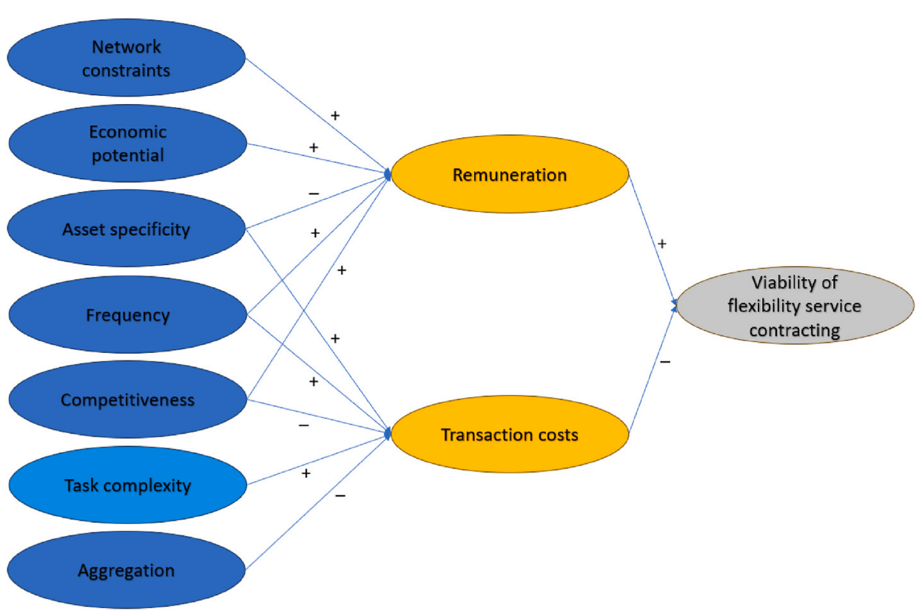

Fig. 1. The flexibility service contracting framework (adapted from [12: 519] and [66: 430]).

Table 3
Transaction costs associated with the task complexity of establishing LEMs and providing flexibility services within (adapted from [12] and [66]).

	Local energy market (relational contract)		Flexibility provision (spot market)	
	Tr_{CL}^{LEM}	Tr_{CON}^{LEM}	Tr_{CL}^{Flex}	Tr_{CON}^{Flex}
Search costs	Scoping flexibility potential, asset owners, and aggregators	Scoping flexibility potential, capabilities, and aggregators	Creating flexibility service contract	Contractually agreeing to flexibility service provision
	Establishing Terms and Conditions	Establishing Terms and Conditions	Launching end-to-end process by sending request	Responding to request
	Verifying flexibility potential	Verifying flexibility potential		Receiving contract notifications
	Preparing end-to-end process	Understanding end-to-end process		Notifying platform of availability changes
	Creating conditions for as many asset owners and aggregators to provide flexibility as possible	Optimizing processes		Receiving instructions
	Signing contract to establish LEM	Signing contract to participate in LEM		Selecting and delivering flexibility service
Bargaining costs	Monitoring flexibility provision	Monitoring loss of income from flexibility provision	Monitoring flexibility provision	Monitoring delivery
				Cancelling service delivery if instructed
Opportunism costs	Flexibility potentials	Market discontinuation	Underdelivery	Providing proof of dispatch
			Overdelivery	Settlement and invoicing
Remuneration			Provided in return for contracted flexibility delivery	Received by contractor for the accurate and timely delivery of flexibility services

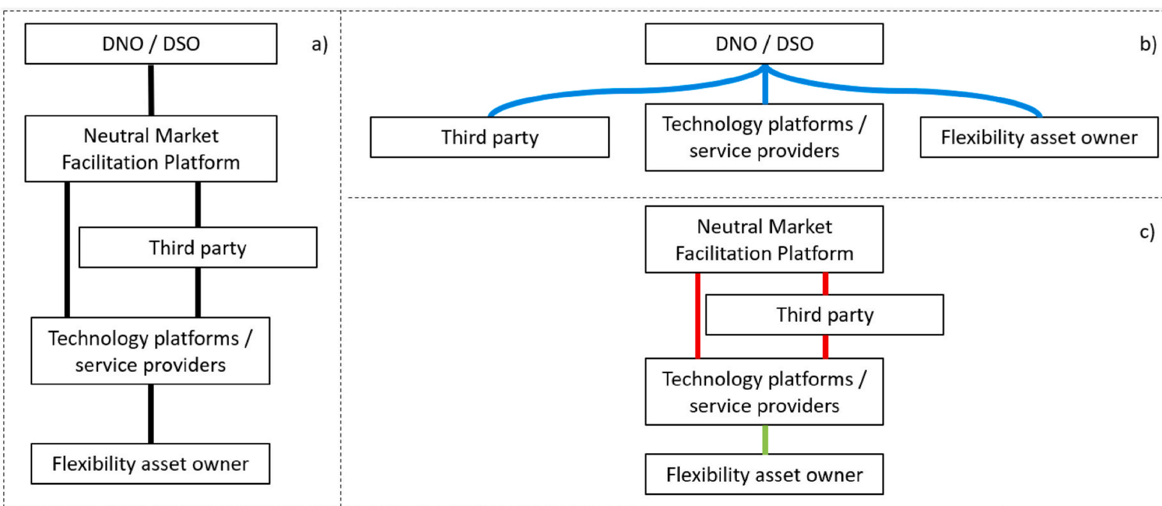

Fig. 2. Structure of the leo local energy market.

services based on their availability (depicted as a green line in Fig. 2c).

In practice, most transactions were conducted through a third-party flexibility exchange platform built by Piclo, a software provider. By interfacing with the NMFP, Piclo's third party platform offered a more streamlined route to participation in local and national markets for flexibility by offering an alternative route for flexibility service providers and aggregators Low Carbon Hub, Oxford Behind the Meter, Nuvve, Origami, and Energie de France (EDF) to bid for flexibility service tenders auctioned by SSEN [76–78]. Regardless of how flexibility was transacted and delivered, however, flexibility provision in such LEMs incurs transaction costs [9–13,16]. Section 4 reviews the viability of procuring the LEM (Section 4.1) and transactions within regarding the costs and remuneration (section 4.2) by testing the model developed above on Project LEO.

4. Findings

4.1. Establishing a local energy market

The starting point for establishing LEMs are *network constraints*. SSEN could defer up to £46m of grid reinforcement costs by procuring 5 GW of flexibility [70]. To determine the flexibility potential through the establishment of the Project LEO LEM, SSEN has had to allocated staff and material (production) costs to develop liquidity indices which provide an overview of how much flexibility is available from partaking assets; to set up the NMFP IT system which advertises the need for flexibility (P_{CL}); and in identifying, coordinating, and contracting with participants capable of supplying the correct level of flexibility at the right voltage level, SSEN has also incurred transaction costs (Tr_{CL}). However, some of these costs were covered by innovation funding and it is assumed that such costs of establishing an LEM will only be incurred once in a geographical area. The *economic potential*, on the other hand, will need to be established by any potential end-use contractor in LEMs. This potential is illustrated using specific data provided by flexibility contractors Low Carbon Hub (LCH) and Oxford City Council (OCC) (Table 4).

However, the *specificity of assets* involved in flexibility service contracting may significantly lower the *economic potential* (Table 5). The resources required to overcome *asset specificity* determine the production costs of LEM contracting for grid-edge flexibility providers (P_{CON}).

Asset specificity determines the actual flexibility potential as opposed to the *economic potential* (Table 5). Using the LCH examples in Table 5, this gap is significant. For example, a 400 kW hydroelectric station in theory suitable for flexibility provision has proven too complex to adapt

Table 4
Economic potential.

	LEM provider (SSEN)	Flexibility provider (LCH)	Flexibility provider (OCC)
Economic potential	Defer up to £46m of grid reinforcement costs by procuring 5 GW of flexibility	97 % of assets are solar PV ranging from school roofs to 19.2 MW Ray Valley site	Building Energy Management Systems
		400 kW hydroelectric station	Air conditioning
		Battery linked to 100 kW hydroelectric station	Chillers
		50 kW battery linked to solar PV system	

while the battery linked to a 100 kW hydroelectric station only draws from the hydro, which is dormant during the summer months. If the latter could access grid power it could provide both Sustain Peak Management (SPM) and Sustain Export Peak Management (SEPM) services (see Annex 1) but the contractual arrangement, and the resulting technical specification, do not allow for this.

End-use energy demand technologies such as air conditioning units and Building Energy Management Systems (BEMS) have also proven more complicated to retrofit for flexibility readiness than anticipated (OCC examples in Table 5). These issues are particularly pronounced in the public sector where expectations of continuous service provision increase *asset specificity* to the detriment of *economic potential*. To sum up, *economic potential* and *asset specificity* are key production cost determinants for the viability of establishing LEMs and determining flexibility potential in general, while the viability of contracting flexibility services in such LEMs is mainly determined by *task complexity* which we analyse in the following section.

4.2. Providing flexibility services

In LEO's proof of concept market, the *task complexity* of relational contracting for flexibility provision was initially determined by SSEN's Flexibility Services Standard Agreement (FSA) [105]. This agreement amounts to 44 pages and is designed for commercial flexibility provision, not public sector, or community organisations with small flexibility potentials, thereby increasing the *transaction costs* for such flexibility providers (Tr_{CON}). In the final stages of Project LEO, a framework-style contract was used alongside the FSA to enable contractors to participate in individual flexibility auctions without the need to sign additional contracts, which allowed flexibility to be procured over shorter timescales and closer to the point of need [106].

Once the contracts have been signed, *task complexity* of the end-to-end process determines the *transaction costs* of providing flexibility services. *Task complexity* is analysed using the example of the time in minutes it takes to complete the end-to-end process (the marginal cost incurred by the flexibility provider M_{CON}^{Flex}) of preparing LCH's solar PV-linked 50 kW battery and delivering up to 15 kW of flexibility at the beginning of flexibility trials in January 2022 and one year later in January 2023 (Table 6). The last column refers to time savings arising from automation using existing technologies which was outside the

Table 6
Marginal cost of community flexibility service task complexity (in minutes).

Task complexity	End-to-end process	Time January 2022	Time January 2023	Time automated
Search costs	Response to request	11	11	11
	Receive contract notifications	1	1	1
	Notify platform of availability changes	6	2	2
	Receiving instructions	22	3	3
	Select and deliver flexibility service	0	0	0
Bargaining costs	Monitor delivery	0	0	0
	Cancel service delivery if instructed	15	5	0
Opportunism costs	Provide proof of dispatch	46	46	2
	Invoicing	15	15	1
	Total	116	83	20

Table 5
Production costs of addressing asset specificity.

	LEM provider (SSEN)	Flexibility provider (LCH)	Flexibility provider (OCC)
	P_{CL}^{LEM}	P_{CON}^{LEM}	P_{CON}^{LEM}
Asset specificity	Staff and material costs associated with developing liquidity indexes to enable an overview of how much flexibility is available from partaking assets	£60,000 capital to make all assets flex ready (including £1000 per inverter to make rooftop solar PV systems flex ready (with a failure rate of around 50 %) plus a sim card at £10 per month)	Improvement of building fabric to improve thermal efficiency and enable flexibility operation over a wider range of outdoor temperatures
	Staff and material costs associated with setting up the Neutral Market Facilitator Platform (NMFP) IT system to be market facing and advertise the need for flexibility	£50,000 capital for platform development (People's Power Station 2.0) to monitor and control for DNO Flexibility	Upgrading Building Energy Management System to enable engagement, not just monitoring
	Staff and material costs associated with setting up the Whole System Coordinator which brings together the need for flexibility derived from SSEN's Power System Analysis (PSA) tool and identify which participants are able to supply the correct level of flexibility	£38,000/year ongoing licence costs of People's Power Station 2.0	£1600 to automate chillers
		£50/hour to operate Platform and deliver for DNO flex markets	Most assets are demand-response which provide 'DSO flexibility services'
		97 % of assets are solar PV which can only provide 'optional downward flexibility management'	Air conditioning in library not possible when temperatures exceed 28C or 20C when it is not operational
		Battery linked to 100 kW hydroelectric station only draws from hydro and does not provide flex services	
		400 kW hydroelectric station too complicated to flex	
		Battery charging which needs to be actioned at least 1 h before flex provision	

Table 7
Remuneration for community flexibility services.

Asset	Flexibility services	Trial period1		Net income
		Revenue	Cost	
Rose Hill Battery	**SEPM & SPM**	£259.50	-£816.32	-£556.82
Rooftop solar	**SEPM**	£52.01	-£394.00	-£341.99
Ray Valley solar	**SEPM**	£850 (forecast)	-£661.00	£189.00

scope of this proof-of-concept project.

Automation has already lowered *task complexity* in the case of the LCH battery by 29 % from 116 min in January 2022 down to 83 min in January 2023. With current automation technology, these temporal *transaction costs* can be lowered down to 20 min, an 83 % reduction relative to January 2022 and a 76 % reduction relative to January 2023. Once the response to request is automated, this can be brought down to 9 min (92 % and 89 % respectively). Such gains will push the viability of flexibility service contracting in LEMs ever closer to the grid edge where *remuneration* (R) is smallest relative to *transaction costs* (Tr_{CON}).

However, *remuneration* during the second trial period, which is calculated by aggregating settlement reports and using commercial templates, rarely exceeded the *cost* of flexibility service provision, let alone operating the People's Power Station 2.0 (see Table 7; see Annex 1 for details on flexibility services and pricing).

The costs and revenues outlined in Table 7 do not take into account the *production costs* of getting the assets flexibility-ready (P_{CON} Table 5) nor the temporal *transaction costs* (Tr_{CON} Table 6). LCH reckons that around 80 % of costs of participation for the battery and rooftop solar and 60 % for Rye Valley Solar were operational as a result the *task complexity* of the end-to-end process (T_{CON}), which required actors to learn a new skill set to engage in this process. Ray Valley Solar delivered (through curtailment) up to four times the asking amount which represents a significant loss of revenue (lost sales revenue, which is already below wholesale price, and loss of Feed-in Tariff revenue) for the asset owner, thereby increasing the marginal cost of flexibility provision (M).

Furthermore, 'dumb inverters' require upgrading and control automation to make them flexibility ready (P_{CON}). LCH, as mentioned in Table 4, invested in upgrades but a high failure rate has limited opportunities for flexibility provision and resulting *remuneration* (R). This provides evidence that *transaction costs* of providing flexibility services increase the smaller the asset (Tr_{CON}). On the other hand, improving operations by lowering *task complexity* through end-user engagement consequently increases the viability of flexibility provision and accuracy of bidding (Table 6) [21,25,29,57,58]. Similarly, scale through *aggregation* increases the total flexibility capacity relative to *transaction costs* [14,15,32,41,45,51]. If *aggregation* exceeds 1 MW, flexibility services can be provided in ESO flexibility markets which are permanent as opposed to temporal, thereby lowering uncertainty by providing greater overall *remuneration* certainty vis-à-vis *transaction costs*.

In LEMs operating at scale with a large geographical range of flexibility service provision and a high diversity of DSO-procurable services, of participating assets, and *frequency* of procurement horizons, *competition* among such *aggregators* should ensure that small flexibility potentials still amount to significant flexibility potential for the client SSEN [65,76–78]. For end use contractors, on the other hand, bidding close to marginal costs because of *competition* decreases the incentive to exploit the *economic potential* of *specific assets*, especially if *remuneration* is uncertain and *transaction costs* remain high. This provides an incentive to seek scale through *aggregation* by expanding the range of flexibility services on offer (see Annex 1).

5. Discussion

Reviewing project LEO's LEM using the model introduced in section 3.3 suggests that *production* and *transaction costs* arise in two distinct stages, the establishment of the LEM and the provision of flexibility services within. To get to the first stage, contractors need to assess both the *economic potential* (Table 4) and the *specificity* (Table 5) of their assets regarding flexibility provision and readiness. Once this potential has been established and flexibility-readiness has been achieved, asset owners sign a relational contract with the DSO client, and a LEM comes into existence. The second stage involves client auctioning of flexibility requirements and contractor bidding of flexibility provision using short-term (month-ahead), simplified short-term (week-ahead), and sport-market (day-ahead) contracts, depending on the *frequency* of flexibility demand, the *task complexity* of the end-to-end process, and the cost of overcoming *asset specificity* to provide flexibility (Table 6).

Project LEO's LEM proof-of-concept served many purposes in this context: increasing competition to reveal the market price for flexibility; establishing SSEN's willingness to pay for flexibility relative to the cost of grid upgrades (P_{CL}); establishing flexibility providers' willingness to accept SSEN's offer of a certain £/kW of flexibility (R; Table 8); providing a better understanding of bid selection; and revealing how *transaction costs* ($Tr_{CL} + Tr_{CON}$) and potential *remuneration* (R) for the provision of flexibility services compare with the *production costs* ($P_{CL} + P_{CON}$) of getting the technology flexibility-ready. This analysis revealed that the Project LEO LEM did not fulfil the second condition for a viable LEM at this proof-of-concept stage (Table 8 - using the example of LCH rooftop solar from Table 7).

Nevertheless, the LEM created by SSEN as part of LEO proved the possibility of flexibility service contracting in such a market. It also revealed both *production* and *transaction costs* which need to be lowered to increase the viability of such markets and ultimately reduce the cost of reaching net zero. Specifically, *assets specific* to generation or end-use energy services with *economic potential* but lacking in-built flexibility are associated with high capital investments to get them flexibility-ready (P_{CON}; Table 8). Similarly, relational contracts designed for commercial flexibility provision increase the *task complexity* of flexibility service contracting in LEMs (Tr_{CON}; Table 8). With *task complexity* of the end-to-end process still comparatively high (Table 6), *remuneration* low (Table 7), *frequency* uncertain, and scale in terms of *aggregation* lacking, the economics of flexibility contracting in LEMs are unfavourable from an end-use contractor perspective:

Table 8
Second condition for a viable LEM.

LCH Rooftop Solar								
R^{Flex}	$>$	$(P_{CON}^{LEM}$	$+$	$M_{CON}^{Flex})$	$+$	$(Tr_{CON}^{LEM}$	$+$	$Tr_{CON}^{Flex})$
£52	$<$			£394				
		£1000 per site to get assets flex-ready		80 % operational cost (can be reduced with automation)		FSA contract		Framework contract
		£38,000/a ongoing licence cost of PPS2.0 (including SIM costs)		10 % SIM card cost of £10/month				
				10 % inaccurate bidding				

"Our revenue for TP2 has been [...] lower than what we, in terms of staff cost, spent on working on it" (Project Partner at Oxfordshire County Council)

"We found that it was very difficult creating a business case for flexibility, because we don't know how many flexibility events there'll be, and we don't know what the prices will be in a competitive market" (Project Partner at Low Carbon Hub)

On the other hand, both the establishment of LEMs, from assessing flexibility potentials to agreeing to relational contracts, and the end-to-end process of delivering flexibility, revealed ample opportunities to lower *transaction costs:*

"If you look at it just based on the actual costs just now for the system as it stands versus the offering that they get, the numbers don't add up. Now, I don't think that's necessarily a bad thing to recognize, I think we need to step back and realize that this is a proof of concept" (Project Partner at SSEN)

Chiefly among these opportunities to lower costs are standardisation to simplify the *task complexity* of assessing *economic potential* and addressing *asset specificity*; regulation to lower the *task complexity* of relational contracting to establish LEMs; automation to lower *task complexity* of end-to-end process delivery; *aggregation* among contractors to create economies of scale and lower contractual complexity; and increasing the *frequency* of flexibility demand in such markets.

- Standardisation especially of industry guidance and interoperability protocols to simplify the collaborative governance of procuring flexibility markets and flexibility services:

"What would be useful for local authorities who are working on public sector decarbonization projects, and upgrading our systems is to understand what exact control systems are required to be able to participate in flexibility [...] we've stuttered and stumbled upon trying to understand what would work , it would be good to have a standard format saying these are the systems that you need" (Project Partner at Oxfordshire County Council)

- Regulation including legal documentation of contractual arrangements:

"I think the work to me is more in the space of the regulatory and the organizational, and in the process side of things [...] I think there's quite a lot of regulatory development needed between the different organisations to understand really, when the dust settles, who performs which role" (Project Partner at SSEN)

- Automation by accessing data from smart meters and routine behaviours rather than dynamic notifications lowers transaction costs of flexibility provision:

"The diversity of assets that don't always have these data communications will cause inherent problems, and we saw that in Sackler [library] where the building management system literally you had to go in and take a USB to pull the data from there. So doing any sort of flex trial on an automated basis from a request from a DSO was just simply not possible." (Project Partner at University of Oxford)

- Aggregation to lower transaction costs for both flexibility providers (market actors) and DSOs by providing a single point of contact to procure and settle flexibility services:

"[By working with an aggregator] the number of customers you engage with, the number of contracts obviously goes down to one [...] So I think for me the offering through the aggregator is critical" (Project Partner at SSEN)

Interestingly, several participating organisations reported non-financial motivations (value propositions) for participating in flexibility markets which might outweigh *transaction cost/remuneration* imbalances if the *transaction costs* of accounting for these benefits do not outweigh them [51].

"It would be a really exciting space to free up a lot of [grid capacity] – because we believe, and we're most interested in it, because we believe that it means that more low carbon technologies will be able to connect to the grid, especially in constrained areas" (Project Partner at Low Carbon Hub)

"Flexibility - it's one of the key measures to be able to make that shift to the renewables-based energy system that we know we need, and that was very much the driver for us as a County Council for participating in the project" (Project Partner at Oxfordshire County Council)

Frequency of flexibility demand in LEMs also needs to be taken into account when considering the economics of flexibility service contracting. Ultimately, the DSO's decision to reinforce the grid can lead to the termination, or at least a significant alteration, of such markets. Without an assured market for flexibility services and predictable demand for such services within, however, the *production* and *transaction costs* of getting assets and participants flexibility-ready (addressing *asset specificity* and *task complexity*) are likely to outweigh infrequent *remuneration*. This is particularly relevant in the context of different payback horizons and investment environments between investment in reinforcement and infrastructure on the one hand and flexibility on the other.

Investments in infrastructure (i.e., reinforcement of the network or transmission system or in large generation assets) generally have a 25-30-year investment horizon. Capital investors in network infrastructure are also assured of income because investment is approved via a regulatory framework and repayments on the investment are socialised. Investment horizons (i.e., visibility of income) offered by procurers of flexibility, on the other hand, are at most 1–2 years under current market conditions in GB [76,78,106]. It can be safely assumed that nobody would invest if all they could see is a 1-2-year horizon for something that might take 15 years to yield a return.

While this paper has benefited from a unique insight into the flexibility of energy service contracting in the LEM created as part of Project LEO, the underlying analysis is necessarily limited by the project duration and boundedness. In such experimental and temporary markets, potential *transaction costs* savings and *remuneration* potentials are evident but their magnitude impossible to predict. It also cannot take into account the structure of LEMs if they are not 'retrofitted' onto existing infrastructures but instead structurally evolve with socio-technical flexibility capability. For example, if heat pumps in future had an in-built flexibility margin which could be contractually accessed remotely by ESCOs, flexibility providers, or DSOs, the *production costs* of establishing LEMs and the *transaction costs* associated with both *asset specificity* (Table 5) and *task complexity* (Table 6) would be significantly reduced.

This paper also barely touches upon the drivers for different actors to engage in flexibility service contracting. The above quotes by Project Partner at Low Carbon Hub and Project Partner at Oxfordshire County Council suggest that some organisations are intrinsically motivated to operationalize such markets as they are not driven by profit maximisation. This requires further exploration to understand how best to structure LEMs vis-à-vis the willingness of end-users to engage [21,25,29,57,58]. To optimise the evolution of flexibility service contracting, research thus needs to shift from this paper's limited focus on a retrofitted 'proof-of-concept' markets towards the economics underpinning embedded markets comprising a rapidly evolving range of technologies with in-built flexibility potential and users potentially more interested in public value than commercial gain.

6. Conclusion

The modified theoretical model introduced in this paper enables the comparison of the relative magnitude of transaction and production cost variables arising from establishing LEMs and providing flexibility services within. By applying it to Project LEO's LEM, this paper identified a range of system cost savings for DSOs with regards to network reinforcement, the transaction costs which arise during the end-to-end process of both procuring and delivering flexibility in LEMs, the contract revenues, and transaction cost savings. Crucially, it sheds light onto uncertainty regarding the value and associated remuneration of flexibility service contracting in time-limited LEMs vis-à-vis production costs of investing into human and physical assets to make them flexibility-ready and the transaction costs of the end-to-end process of delivering flexibility. At this proof-of-concept stage, both these production and transaction costs limit the scope and depth of flexibility service contracting, especially when assets need costly retrofitting for flexibility-readiness. On the other hand, the economics of flexibility service contracting in LEMs can be significantly improved through automation, aggregation, standardisation, and regulation.

Automation improves the time effectiveness of the end-to-end process and spot-market transaction; aggregation of flexibility capacities creates economies of scale and reduces the contractual complexity; standardisation streamlines communication between different platforms; and regulation created the requirement or incentive for different actors to improve these other factors. Furthermore, if the business case was thus rendered more viable for the delivery of ESO flexibility services, the additional transaction costs of flexibility contracting in LEMs would be marginal and such service provision might improve the overall business case of flexibility contracting.

Significant market distortions such as energy price caps, on the other hand, increase the risk for both suppliers and flexibility providers. In particular, they lower the overall viability of establishing forward markets such as LEMs, especially if such distortions dampen temporal price swings resulting from the technological supply mix, as opposed to external factors such as geopolitical uncertainty. Less blunt mechanisms are required to shield vulnerable consumers while ensuring that temporal price swings remain sufficient to incentivise flexibility provision in LEMs from an increasingly diverse range of sources.

Policymakers should mandate the flexibility-readiness and interoperability of end-use energy technologies such as chillers and heat pumps through standardisation. Business model innovation around aggregation can be supported through the simplification of documentation as opposed to the current Service Standard Agreements. Ultimately, however, trust needs to be built in the longevity of such markets. Rather than imposing price caps, the exploration of zonal and locational pricing is to be welcomed in this context. These could support the emergence of business models partially or even entirely dependent on flexibility remuneration although such pricing needs to be carefully weighed up against potentially detrimental impacts on investment in low-carbon generation technology.

Either way, capturing transaction cost savings alongside production savings and remuneration in maturing LEMs will help lower these costs and expand the scope and depth of flexibility provision. This will facilitate greater grid penetration of renewable energy resources while supporting the wholesale electrification of heating and mobility without relying entirely on costly grid reinforcements. Crucially, flexibility contracting can also contribute to both socialising the benefits and lowering the costs of transitioning to net zero. Such gains are crucial as achieving net zero is increasingly under threat by those arguing against its financial viability.

CRediT authorship contribution statement

Colin Nolden: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **Nicholas Banks:** Methodology, Validation, Formal analysis, Investigation, Funding acquisition. **Jack Irwin:** Validation, Formal analysis, Investigation. **David Wallom:** Validation. **Bryony Parrish:** Methodology, Validation, Formal analysis, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex 1. Summary of DSO-procured and DSO-enabled services and price ceilings

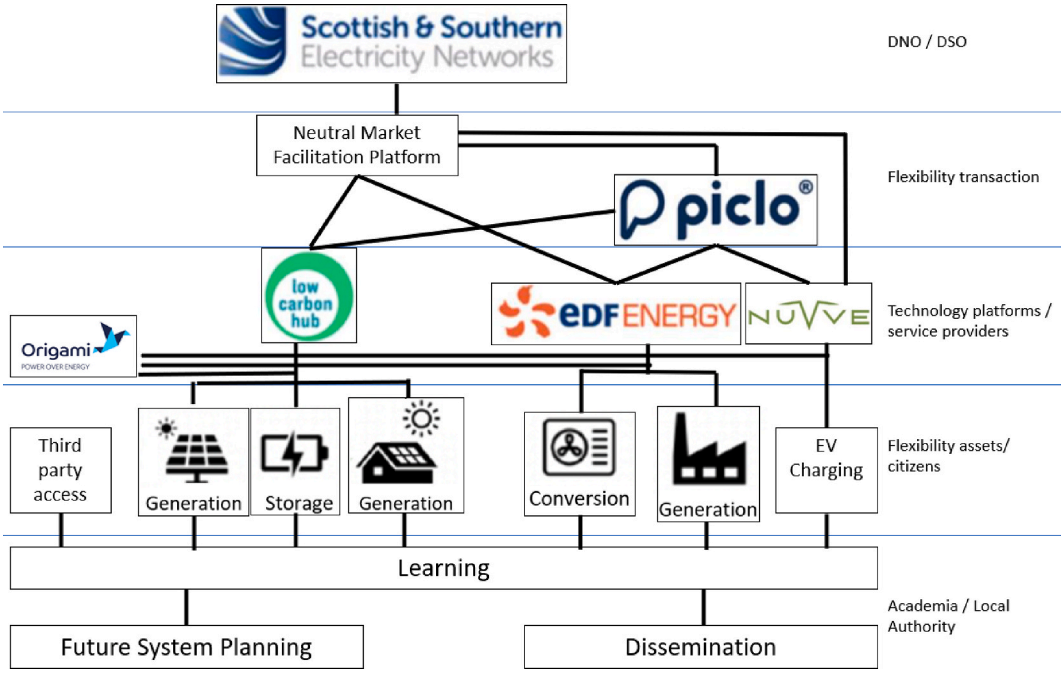

Fig. A1. Structure of the LEO LEM [78: 12–13].

Table A1
Summary of DSO-procured and DSO-enabled services and price ceilings [78: 12–13]

DSO Procured Services		TP2 service price ceiling
Sustain Peak Management (SPM)	A market participant delivers flexibility to the DSO to reduce the demand on a critical DNO asset (such as a transformer) that is forecast to become overloaded due to increased demand.	£600/MWh
Sustain Export Peak Management (SEPM)	A market participant delivers flexibility to the DSO to increase the demand on a critical DNO asset (such as a transformer) when it is forecast to become overloaded due to increased generation.	£850/MWh
Secure DSO Constrain Management (SCM	A market participant delivers flexibility to the DSO to reduce the demand on a critical DNO asset (such as a transformer) that is subject to an emerging issue that could result in an unplanned outage if not addressed.	£800/MWh
Dynamic DSO Constraint Management (DCM)	A market participant delivers flexibility to the DSO after an unplanned outage to help restore electricity to a network area or relieve pressure on the system so it can recover.	£1200/MWh
DSO Enabled Services		
Maximum Export Capacity (MEC)	Two market participants in a network area with limited (or no) spare export capacity trade a portion of their export capacity for an agreed period, without affecting the network. The Buyer can increase their export level, but the Seller must reduce their export level.	
Maximum Import Capacity (MIC)	Two market participants in a network area with limited (or no) spare import capacity trade a portion of their import capacity for an agreed period without affecting the network. The Buyer can increase their import level, but the Seller must reduce their import level.	

Data availability

All data is available at https://project-leo.co.uk/resources.

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