National Centre for Energy Systems Integration

Democratising Energy:

Placing citizens and communities at the heart of the energy revolution

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Democratising Energy: Placing citizens and communities at the heart of the energy revolution

Abstract

Energy communities formed by prosumers are increasingly becoming a promising solution for delivering sustainable energy systems that promote renewable integration and active participation of end-users.

In energy communities, end-users may trade energy with each other and invest in shared assets, such as power generation, energy storage, or shared network infrastructure. Local energy markets (LEMs) and Smart Local Energy Systems (SLES) are emerging as new methods to coordinate assets of distributed power in a local area.

Designs of LEM solutions and citizen-led energy communities differ widely in the literature and present topics of intensive research. Generally, potential benefits provide opportunities for revenue generation or cost reduction for end-users and local communities, provision of market access to small-scale generation and storage, which may untap the value of demand-side flexibility and improve wider network and system management, but depend on the market design.

There are also challenges and risks associated with the adoption of energy communities, most importantly LEMs need to be adopted by end-users.

The key to success is to place the consumers at the centre of the energy revolution and to design solutions that are tailored to local communities and end-user needs, while achieving desired decarbonisation.

Researchers from the UK National Centre for Energy Systems Integration (CESI) have been working intensively to address some of these challenges. CESI is an EPSRC-funded centre that aims to reduce risks associated with securing an integrated energy system for the UK by adopting a multi-vector approach. In this white paper, we examine the expanding range of opportunities that emerge when end-users join forces to form an energy community. Energy or services can be traded locally (peer to community, peer to peer energy trading or trading with local grid) or can be aggregated and sold further in system-wide markets.

Successful roll-out of local solutions requires development of various techniques that enable public acceptance and consumer engagement. CESI models presented in this white paper ensure that:

- Participation in community and LEM initiatives is beneficial to participants
- Consumer preferences with respect to their energy behaviour are captured in models to maximise consumer acceptance
- Fairness of income distribution is promoted
- Revenue can be generated within the community boundary, but also by provision of services (energy and flexibility) to upstream markets
- Effects of local energy management to network and system are assessed.

We discuss key findings of the work undertaken in CESI and identify future directions.

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Problem statement

Net-zero targets and development of low carbon technologies are changing electricity systems. Proliferation of prosumers and distributed generation resources (DERs) are leading to a radical transformation of the centralised energy system into becoming more decentralised, volatile and harder to manage. Consumer-centred business models, such as energy communities, LEMs and SLES, are emerging as promising methods to coordinate generation, storage, and demand-side flexibility in a local area.

In energy communities, end-users may trade energy with each other and/or invest in shared assets, such as generation, storage, or network infrastructure. In this context, how local energy systems are designed and shared, are open research questions that require novel modelling paradigms that place end-users in the centre of the decision-making for the energy system. The challenges that consumer-centred business models are facing and are addressed in this paper are:

- What are the value gains stemming from participation in energy communities or LEMs for different stakeholders (prosumers, operators, system)? Is participation always beneficial?
- Which factors promote consumer participation and adoption of local energy solutions? How can we design systems that consider consumer preferences and needs?
- How are benefits yielded from community initiatives shared among participants?
- How to design viable user-centric business models that promote the adoption of RES and make sustainable behaviours more attractive to prosumers and local communities?
- What are the tools that can support the decentralised energy transition?

Background

Given the emergency our societies face against climate change, nations around the world have mandated net-zero emissions targets. The decarbonisation agenda includes a fundamental shift in generation and supply by moving away from centrally produced carbon-based fossil fuels towards local low-carbon DERs.

The increasing number of DERs is shifting the development of energy systems towards a more decentralised structure, enabling a significant shift in market power from large producers to individual prosumers. Prosumers not only consume energy, but also produce energy from own assets (PVs, batteries, EVs, etc.) and inject it back to the grid. They may also form communities and collaborate to optimise their resources or invest in renewable projects.

On top of consumer empowerment, which is expected to play a greater role in future energy systems, the energy transition is also enabled by the integration of ICT and data technologies to energy systems, which are providing new opportunities for more efficient operation of energy systems [1].

Radical system changes call for new ways to actively engage with prosumers and distributed power investors, who typically act independently according to their own interest.

Financial incentives for RES production such as feed-in tariffs are being reduced considerably and are potentially hindering the pace of the energy transition. In addition, the increase in renewable penetration, results in new challenges for network operation, especially at the distribution level, leading to a need for establishing consumer-centric business models with substantial innovation in the way the local networks are managed and balanced. Promising solutions to manage decentralised and complex systems are LEMs and SLES [2].

While, local energy solutions can achieve a more reliable, resilient and decarbonised energy system, their benefits depend on the actual market design, an issue which is still open to debate. CESI researchers have produced several reports that looked at different market designs [3], impact of LEM in the power network [4] and perceptions of end-users to peer to peer (P2P) energy trading in the UK [5].

Key to achieving desired outcomes, is to design solutions that are tailored to end-user needs and that promote public acceptance and active consumer engagement.

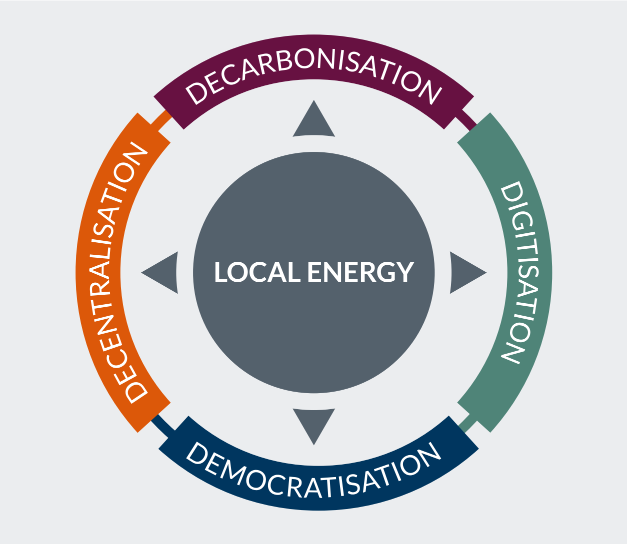

Figure 1: Main drivers for local energy solutions

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Solution

Energy community models and local solutions face numerous challenges for successful roll-out and adoption. Most importantly, these new business models need to be accepted by end-users and need to promote sustainable behaviour, value creation and active engagement. In CESI, we argue that there are several key objectives that need to be met to achieve these goals. These are:

1. **Value creation**: Participation in energy communities and LEMs needs to be beneficial and should enhance local energy management by promoting better matching of local generation and consumption. Value lies in increasing self-consumption, reducing energy bills, and creating new streams of revenue by providing services to the grid via access to existing (wholesale energy or ancillary services) or new markets (DSO-based flexibility markets). No streams of potential revenue should be left out of consideration to increase the viability of prosumer business models and possibly achieve bundling of multiple revenue streams or value stacking. Value creation should also benefit network and system management.

2. **Alignment to end-users needs**: Energy is often treated as a homogenous product; however, research indicates that end-consumers may experience preferences related to the energy source or destination, they may prefer several RES technologies over others or may prefer trading energy with peers from their community. Sustainable behaviour is influenced by end-user values, such as care for convenience, individual interest or care for others or the environment. Capturing and integrating heterogenous preferences of end-users would therefore increase consumer acceptance.

3. **Fairness and equitability of realised benefits**: Equality is of great importance in many aspects of human society, including how energy is managed and crucially how income distribution is shared among prosumers. Lack of equality would lead to disproportionate income distribution hindering acceptance and adoption of local solutions.

4. **Utilisation of state-of-the-art multi-disciplinary techniques**: New control methods and modelling paradigms are required for decentralised grids with significant embedded generation that are applying novel business models applicable to operational decisions (e.g. community trading) or shared infrastructure. Such techniques include multi-agent systems (MAS), distributed artificial intelligence (AI), optimisation, game theory and ICT techniques for modelling decentralised, strategic behaviour, and local decision-making of prosumers. Further, modelling should be able to include enabling digital governance technologies (such as blockchains) that empower end-users to take control of their energy decisions.

Researchers at the National Centre for Energy System Integration have proposed modelling tools, solutions and frameworks for SLES and energy communities that fulfil the above requirements. A summary of the relevant works and models is shown in Fig.x and a brief description on each model is presented in the following section.

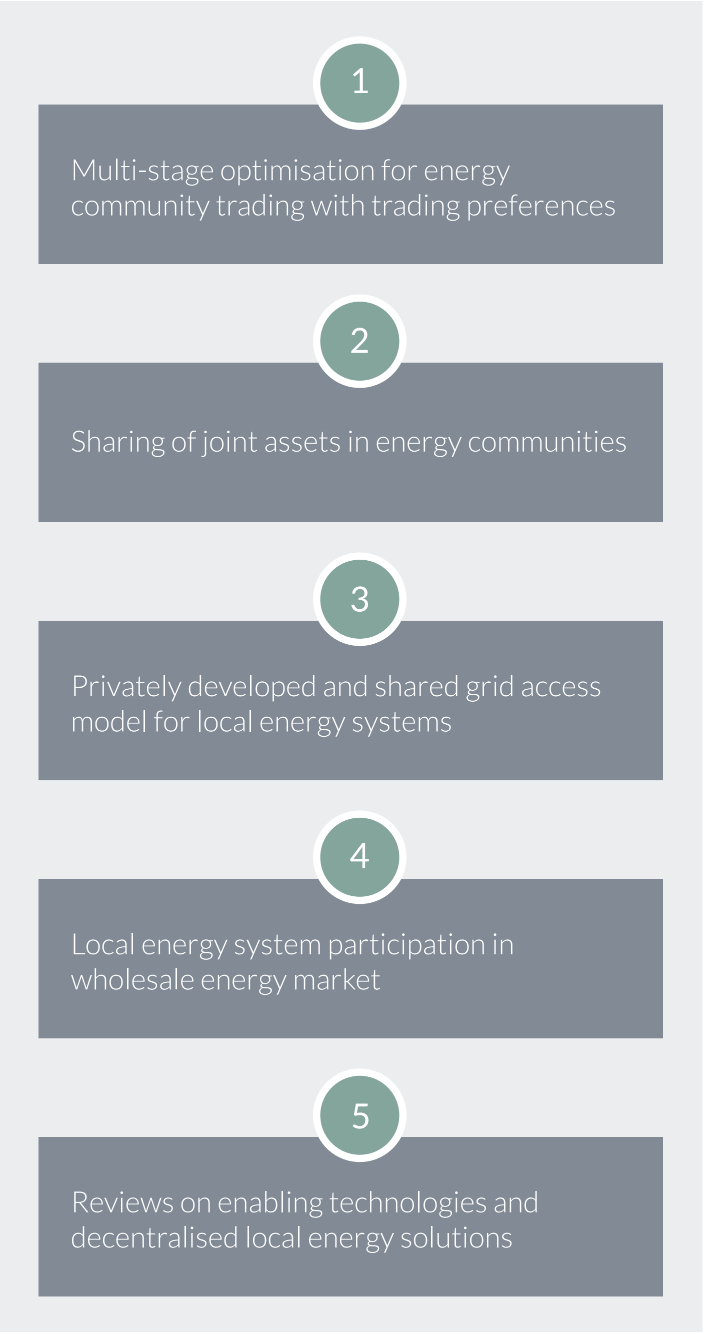

Figure 2: Overview of CESI work related to local energy solutions and smart local energy systems

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I) MAS model for day-ahead energy community trading based on prosumer energy preferences

MAS modelling is way of testing (through simulations) how complex system behaviours emerge from local decision-making and a large number of agents. In our model, a software agent encodes the decisions of a prosumer (household) and its energy preferences and information.

In the conventional way of trading, prosumers buy and sell energy via an energy supplier. In this model, they trade energy with local peers and the process is coordinated by a community agent. Agents (prosumers) may have generation and flexible demand, such as smart appliances, batteries or EVs, which they may be willing to shift. Energy management is realised via a multi-stage optimisation process.

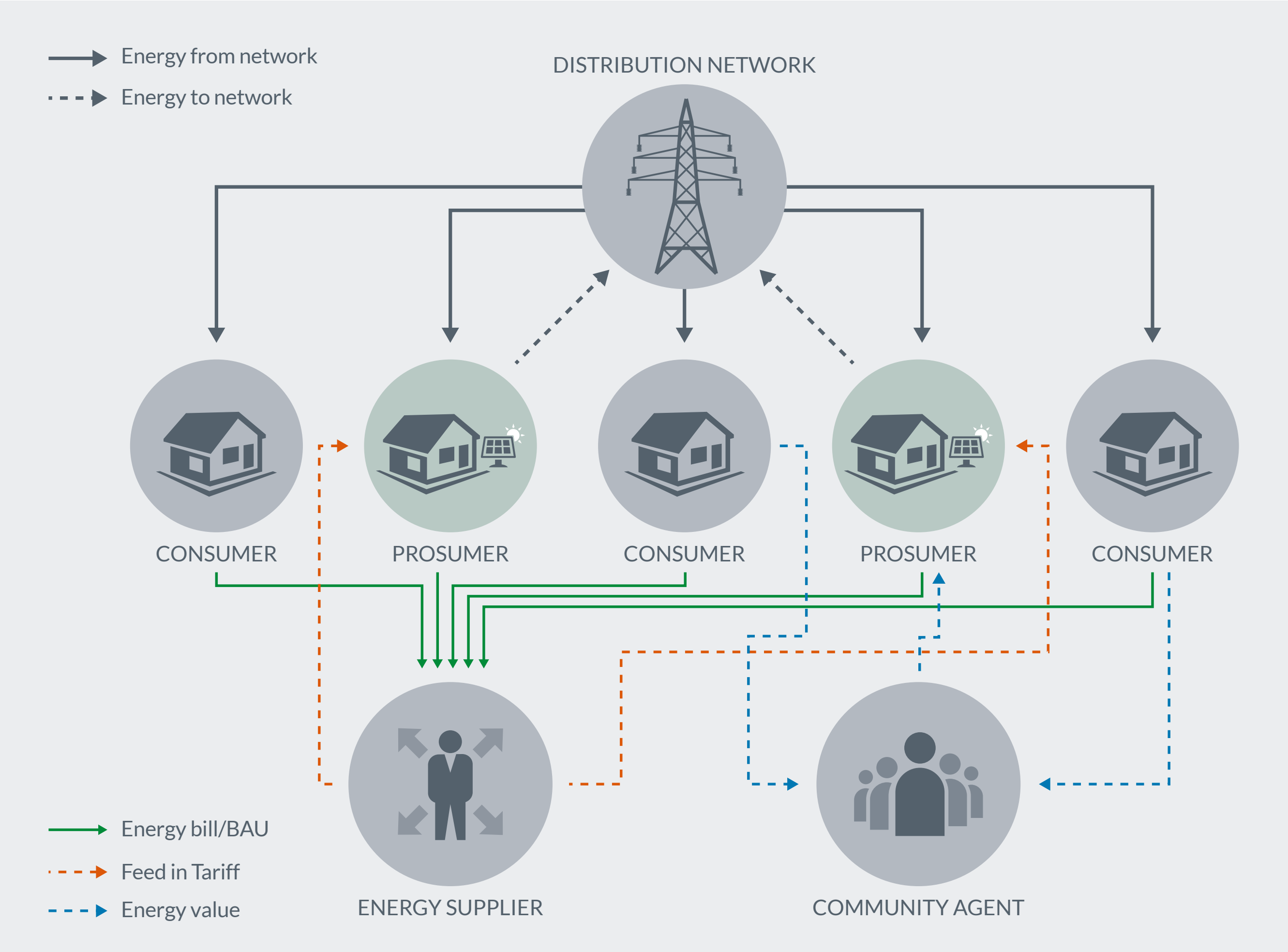
At the first stage, super-local matching of energy is achieved at a household level. Then excess generation and flexible demand is made available and optimised at the community level. Finally, at the third stage agents optimise demand and trades with the wider main grid.

Local energy solutions need to capture heterogeneous preferences and models need to simulate implications of such preferences to aggregate effects at the local level. In this work, preferences are captured by assuming different classes of end-users, each acting to optimise their own objective: cost-driven agents act to minimise energy bills, low-carbon agents to consume more green energy and social agents to maximise peer trading.

The model is a flexible tool to simulate scenarios for current and future energy systems with different agent types, flexibility, RES penetration etc.

Comparison of conventional trading with community trading based on 210 households from the Findhorn community (CESI demonstrator) shows that all agents benefit from participation in the market, maximum values of grid exports/imports and self-consumption of locally produced green energy are shown to improve.

The model also shows how benefits are distributed between prosumers and consumers of different classes and when are the critical points when adding more participants to the market does not add additional value.



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II) Modelling economic sharing of joint assets in energy communities under LV network constraints

Energy community projects often involve jointly-owned assets, but given that not all community members have the same size, energy needs or demand profiles, a key challenge is how these assets can be efficiently controlled in real time and how the energy outputs from these jointly owned assets should be shared fairly among community members.

Crucially, such real-time control and fair sharing of energy must also consider the technical constraints of the network.

To address these challenges, we provide new algorithms for smart control of energy assets and redistribution mechanisms, based on the marginal contribution of each household, that yield to fairer ways to divide joint gains, using tools from distributed AI and cooperative game theory [6], [7].

The redistribution mechanism is fair and scalable. Results based on 200 houses from the ReFLEX project, the UK's largest smart energy demonstration project and CESI demonstrator, show that community-owned assets provide a lower annual bill, and that redistribution method yields to a greater reduction of the annual bill for 67% of the community households compared state-of-the-art methods.

Large consumers benefit slightly less under this scheme, but they still obtain the highest bill reduction in value as compared to households with lower demand profiles. Therefore, the proposed redistribution mechanism achieves a fairer redistribution leading to greater social acceptance, key to incentivising more communities to form coalitions and invest in jointly-owned renewable energy assets.

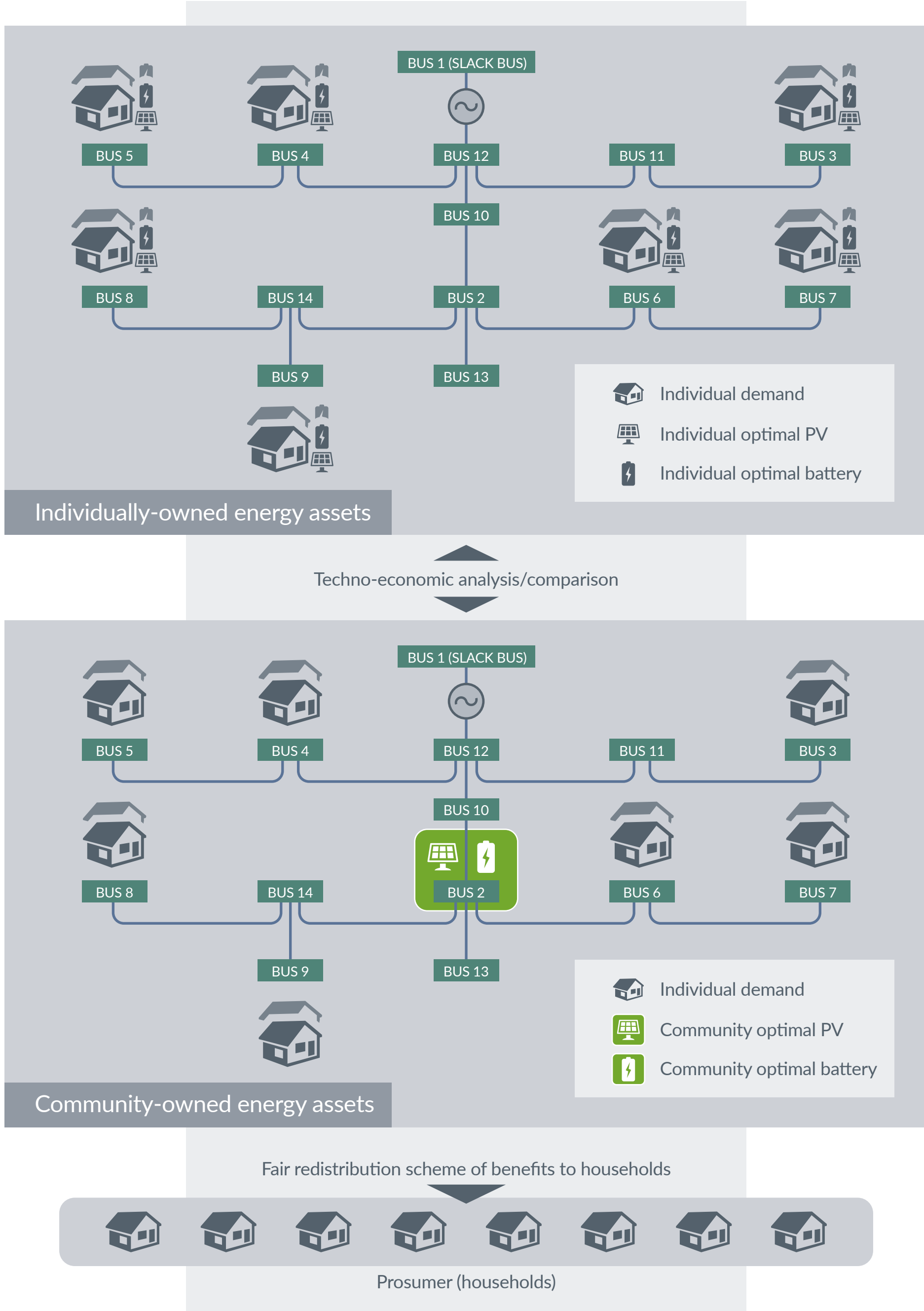

Figure 3: Overview of energy community modelling

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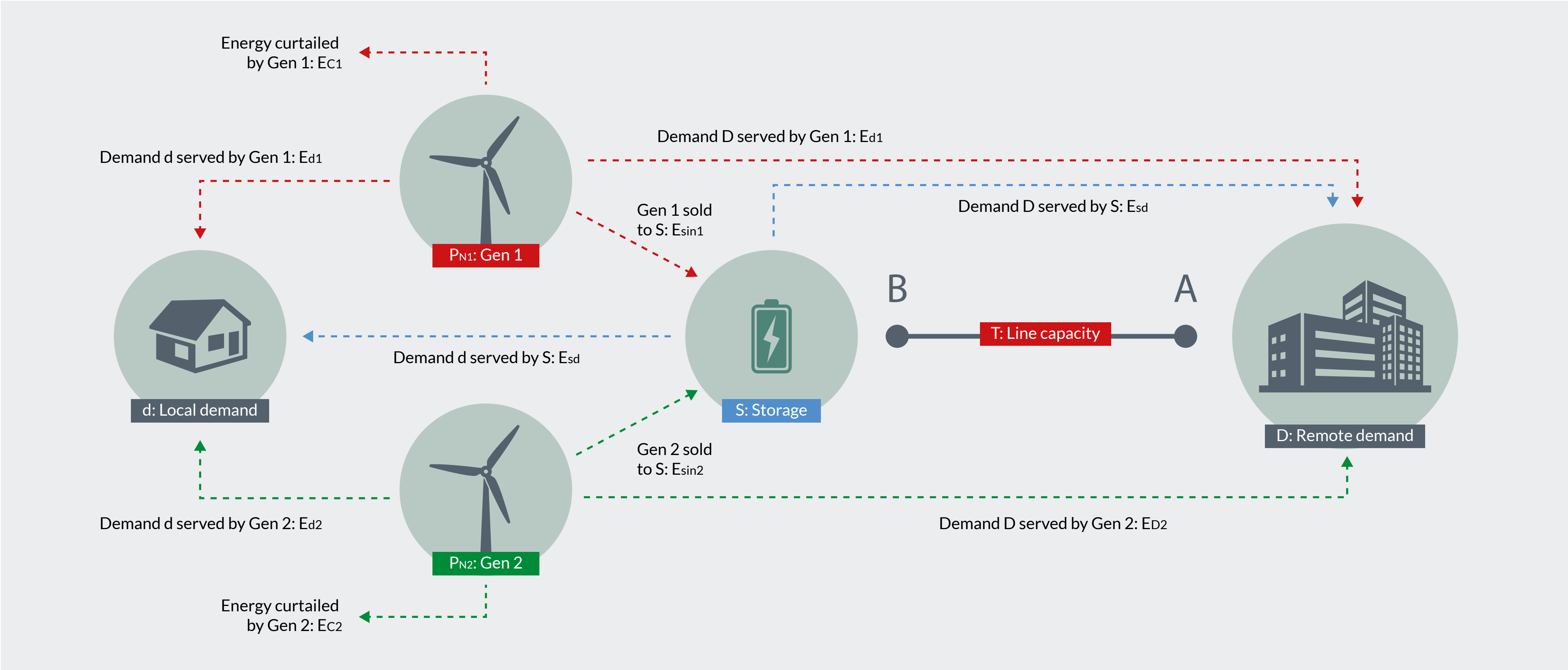
III) Privately developed and shared grid access model for local energy systems

Local energy systems are usually connected via the publicly available grid infrastructure.

However, as the penetration of distributed generation increases, local grids are placed under stress leading to restricted connections, increasing curtailment and delays in required network upgrades. Another possibility emerging as an alternative route to obtain network access, is the model of privately developed and shared grid infrastructure [8].

Such models involve complex decision-making by self-interested private investors leading to strategic behaviours that need to be modelled by game-theoretic models. In this work, profit-driven investors build power grid infrastructure, renewable generation and storage units. Specifically, we consider a case where demand and generation sites are not co-located, and a private investor installs generation capacity and a power line between the two locations providing also access to rival competitors (local generators and storage investors) against a fee.

We then develop a data-driven solution to derive the profit-maximising optimal capacities of renewable generation and storage installed by players at equilibrium of this competitive game, based on analysis of a large-scale empirical dataset from a grid upgrade project in the UK. The methodology provides a realistic mechanism to analyse investor decision-making and investigate feasible tariffs that encourage distributed renewable investment, with sharing of grid access.



IV) Real-time control of distributed batteries with blockchain implementation

Integration of RES could be accelerated with home battery energy systems, however, these are currently not cost-effective, highlighting the need for new business models that would increase the viability of distributed generation and storage.

Apart from self-consumption, storage systems can provide grid or system services, enabling a multi-use approach and promoting value-stacking of energy storage. One solution is for batteries installed at individual houses in a community to participate in the wholesale energy market via a community agent or aggregator, as shown in this work.

The model developed allows for multiple objectives: i) at individual consumer level to maximise local energy self-consumption and ii) at aggregator level to ensure that the fleet of aggregated small-scale domestic batteries participates profitably in wholesale markets.

Designing algorithms that can handle these often-conflicting objectives in real time with many distributed assets is a challenging problem, which requires a multi-layered approach and control solution.

Using minutely data for 70 residential batteries from the ReFLEX case study [9], results indicate that the proposed method increases the aggregator's revenues by 35% compared to a case without residential flexibility and increases the self-consumption rate of the households by a factor of two. Moreover, the framework developed is implemented in a blockchain-enabled smart contracts platform that coordinates the individual households' exports. The blockchain platform also facilitates the settlement phase and distribution of income earned to individual households.

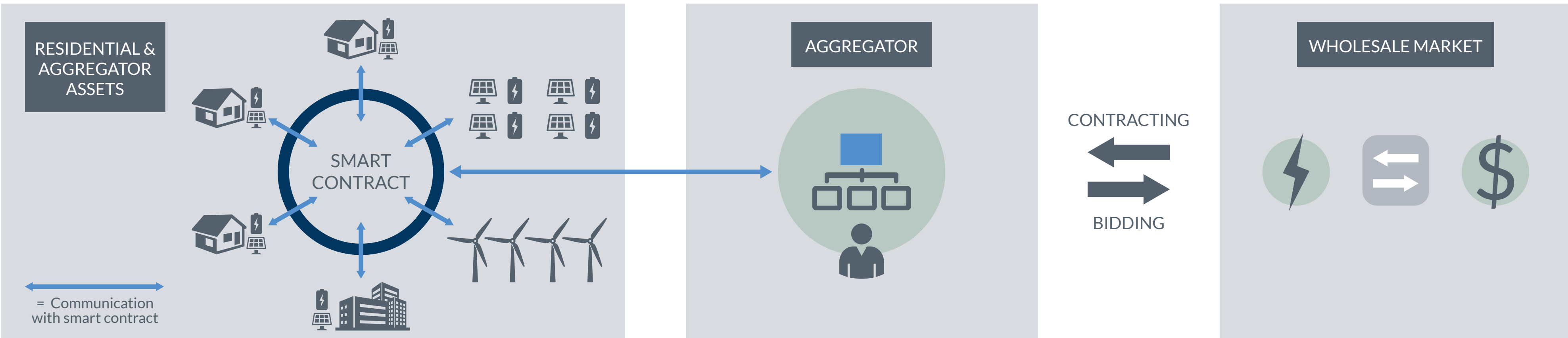
V) CESI reviews on enabling digital technologies and decentralised local energy solutions

The energy transition and adoption of local energy solutions requires the combination of several interdisciplinary techniques including digitalisation techniques. Distributed ledger and blockchain technologies have been reported as great enablers of local decentralised energy systems.

Blockchains are shared and distributed data structures or ledgers that can securely store digital transactions without using a central point of authority. Yet, as their potential is not fully realised, CESI commissioned several reports that looked at blockchain technology use cases [10] and use of smart contracts for the energy sector [11].

Moreover, CESI looked at AI techniques for unlocking residential flexibility and demand response [12].

Specifically, in the field of local energy and community trading, CESI researchers produced several reports that looked at different local energy market designs [3], emerging business models of LEMs [13], the impact of decentralised P2P energy trading models in the power network [4] and a review based on consumers surveys and interviews on the perceptions of end-users to P2P energy trading in the UK [5].



Conclusion

LEMs and energy community projects can support the coordination of distributed generation, demand-side flexibility and consumption in local energy systems and can incentivise active participation of end-users to energy markets.

We have just started to realise the potential of local solutions and their importance for delivering a sustainable future for local communities.

Beneficial outcomes of such models include provision of market access to small-scale prosumers, opportunity for end-user revenue creation from energy and flexibility trading and improvement of network management.

However, these benefits rely heavily on the actual market design, price formation and rules for trading. Ongoing research is required to ensure that local solutions have no unintended consequences on other system users or wider system balancing.

For example, as dependency on the main grid decreases this might lead to increased costs for consumers out of the local community.

Moreover, LEMs might unintendedly add an additional level of complexity, which may lead to harder system management.

There are other areas of future research including work on revenue stacking to improve the business case for local energy communities, incorporating uncertainty consideration in our modelling, strategic behaviour from end users, assessment of the flexibility potential at a local level, quantification and remuneration of grid services provision, consideration of multi-vector analysis etc.

Appropriate design of local systems will also require further research in other areas than traditional power systems research, including data-driven techniques, AI, automation, new technologies of data governance etc., but also more research to understand the role of consumers, their preferences and needs. Only then LEM solutions would work for and be adopted by consumers.

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