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Review article

Defining characteristics of peer-to-peer energy trading, transactive energy, and community self-consumption: A review of literature and expert perspectives

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ABSTRACT

To facilitate a successful integration of distributed energy resources into the electricity generation mix, new forms of energy markets must be considered. Concepts such as Peer-to-peer energy trading (P2P), transactive energy (TE) and community/collective self-consumption (CSC) are frequently mentioned as solutions to this challenge. Despite increasing interest from industry, policy, and academia, the field lacks a shared understanding of this class of models. This need is addressed by presenting sets of shared and distinct characteristics which define P2P, TE and CSC. Our analysis is based on a series of expert group interviews with regulators, industry, and academics across 13 countries, and a systematic and targeted literature review of 133 papers. Findings show that P2P/TE/CSC models can be described as sub-markets that operate within or alongside traditional energy markets and enable trading or sharing of energy using an automated approach. They focus on promoting and supporting local energy generation and consumption using price negotiation mechanisms that reflect the aims of the market. The paper also presents sets of characteristics which differentiate P2P, TE, and CSC from one another and sets out guiding definitions to be used as a reference point. The main differences between these models stem from the goal they are trying to achieve and the contexts they are deployed in. Findings from this analysis can support development of a shared understanding of this class of models across multiple disciplinary perspectives and applications.

Contents

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Nomenclature

API	Application programming interface
CSC	Community or collective self-consumption
DER	Distributed energy resource
DLT	Distributed ledger technology
GO-P2P	Global Observatory on Peer-to-Peer, Community Self-Consumption and Transactive Energy Models
LEM	Local energy market
LV	Low-voltage
P2P	Peer-to-peer
PV	Photovoltaic
RED II	Renewable Energy Directive II
RES	Renewable energy source
SI	Similarity index
TE	Transactive energy
VPP	Virtual power plant

1. Introduction

The increasing deployment of Distributed Energy Resources (DERs) to meet carbon reduction targets poses enormous challenges to the traditional energy supply system, which has been previously characterised by few centralised generation units with high reliability. Focus has shifted towards decentralised energy management, given the increasing availability of decentralised renewable generation units, storage facilities, and electric vehicles. As energy end users become more active in their generation and consumption behaviour, their traditionally passive role in the energy market must be reconsidered [1]. Currently, domestic consumers with DER assets, known as 'prosumers', do not have a platform for active participation in energy services, meaning that they remain an untapped source of potential for future energy systems [2].

In response, decentralised or local energy markets (LEMs) have been proposed in academic literature and trialled in real-world pilot projects [3,4]. Regulators and policymakers globally are working with tools such as regulatory sandboxes [5] to understand how these markets can be incorporated and harmonised with existing energy market structures [6,7]. The challenge is to democratise and decentralise energy markets by allowing new market participants to contribute whilst at the same time ensuring system stability and reliability. Commonly referred to models of LEMs include, but are not limited to, Peer-to-Peer Energy Trading (P2P, or 'peer-to-peer'), Transactive Energy (TE) and Community or Collective Self-Consumption (CSC). These models share similar underlying concepts but have differences in their key objectives. Regulation of these models must balance creating a supportive environment for innovation with ensuring consumer protection. There are several unresolved regulatory barriers in this field, such as the 'single supplier model', challenges related to data sharing, and the lack of defined rights and responsibilities for prosumers (see [7] for comprehensive discussion).

Despite the industry, policy, and academic attention P2P, TE and CSC models have attracted, the field lacks a shared definition of this class of models. The research presented in this paper was conducted as part of the Global Observatory on Peer-to-Peer, Community Self-Consumption and Transactive Energy Models (GO-P2P), a task of the User-Centred Energy Systems Technology Collaboration Programme (Users TCP), which runs under the auspices of the IEA (International Energy Agency). GO-P2P is a forum for international collaboration for academic experts, industry innovators, policymakers and other stakeholders across multiple disciplinary backgrounds, which aims to understand the policy, regulatory, social and technological conditions necessary to support the wider deployment of P2P, TE and CSC models. The key aim of GO-P2P is to collect data from pilots of P2P, TE and CSC and run an international comparative analysis to find out what are the enabling and inhibiting factors for the rollout of these models. To understand which pilots to include in this work and to categorise them, it is necessary to understand the defining characteristics of P2P, TE, and CSC [8].

Knowledge gained from GO-P2P shows that terms are often used interchangeably or inconsistently across different pilot projects, geographical locations, and policy contexts. This condition partially stems from the nascent and highly applied nature of this field: Firstly, this is an evolving field and the specific time period in which a term originated can influence how it is understood as technologies and knowledge develop. Similarly, where a term has originated in relation to a particular location it can guide how a term is used and understood in the particular regional or national context, particularly if academic researchers or innovators attempt to align their work with current policy priorities. Finally, this is a cross-disciplinary field: the disciplinary perspective from which a term originates can impact the main focus of its definition. The combination of the three factors – time period, geographical location, and discipline – can result in a multiplicity of definitions that might or might not refer to the same concept.

A shared understanding of these concepts is a basic prerequisite to allow knowledge exchange between industry and academia, avoid misconception and encourage synergy effects. There have been attempts at providing definitions for P2P, TE and CSC, usually led by larger organisations in the field [9,10]. Appropriate concept definition is essential for policy-making, given that countries are already starting to draft legislation enabling P2P, TE and CSC models to be developed (e.g., [9]). This will enable collaboration between sectors, as well as exchange of best practices at national and international level. Nonetheless, most definitions focus on a single aspect of the concepts, rather than a holistic examination of all aspects of these models. There have already been several comprehensive systematic reviews P2P, TE, and CSC systems [7,11–14]. However, these reviews aimed to identify evidence gaps from a particular perspective, rather than to bring together a holistic understanding of these models.

This paper meets this need by addressing the following research question: *What are the key defining characteristics of energy systems labelled as Peer-to-Peer Energy Trading, Community/Collective Self-Consumption or Transactive Energy as outlined in the literature and by stakeholders?* To answer this question, the following aims are addressed:

1. To understand which characteristics distinguish P2P, TE, CSC models from traditional energy systems.
2. To understand which broader terms are being used in the literature to refer to P2P, TE, and CSC-type models and how similar they are to one another with regards to the number of characteristics they share.
3. To understand which characteristics are associated with P2P, TE, and CSC respectively, and where the similarities and differences between them lie.
4. To reflect critically on how the terms P2P, TE, and CSC are being used and understand implications for the sector.

Given the breadth and evolving nature of this field, providing a comprehensive review of all definitions is challenging. Instead, this paper brings together multiple data sources to reach an informed and shared understanding of how these terms are being used across different disciplines and contexts. Five expert group interviews with academics, industry, and policy representatives in 13 countries were conducted to identify key defining characteristics that distinguish P2P, TE and CSC models from traditional energy systems. This was followed by systematic and targeted reviews of academic and grey literature to determine how these terms are used in the field, and identified characteristics to distinguish the three models from one another.

The paper is structured as follows: Section 2 describes the overarching methodology of the paper including the data collection process for expert interviews and literature review. Section 3 presents results from the expert interviews, which aimed to understand which features a pilot would have to exhibit to belong to this class of models. Section 4 presents results from the systematic and targeted reviews, which aimed to identify characteristics that distinguish P2P, TE, and CSC from one another. Section 5 discusses findings and presents guiding definitions. Section 6 concludes by offering a future outlook and recommendations.

2. Methodological approach

In this paper, semi-structured expert group interviews with a systematic and targeted review of academic and grey literature are combined, in order to capture diverse perspectives and allow the strengths of each method to overcome the limitations of the other. Specific methods are outlined in the subsections below.

This approach borrows from the field of terminology science, which is concerned with how terms develop and evolve in practice. It specifically borrows from 'textual' (also called 'corpus terminology') and 'socioterminological' approaches [15]. The ISO/TR 22134:2007 'Practical Guidelines For Socioterminology' defines socioterminology as an "...approach of terminology work based on the sociological, cultural and sociolinguistic characteristics of a linguistic community, aiming at the study and the development of its technolects in accordance with those characteristics". In other words, socioterminology looks to understand the technical language of a subject or field by examining various aspects of its use by the community's experts. Socioterminology begins with an analysis of discourse within the field of study (either written or spoken) to construct "textual corpuses corresponding to the various scientific, technical and professional communication situations". These corpuses are then analysed to understand discursive practices relating to how terms are used within the field [16]. This is reflected in the expert group interview work conducted in this paper. Textual, or corpus, terminology "consists of examining the corpus of texts produced freely by experts in a field in order to extract from it significant factors that enable the concepts to be reconstructed and to extract the data essential for drafting definitions, and terms or "candidate terms" that designate the concepts" [16]. This approach is reflected in the literature analysis conducted in this paper.

Table 1
Number of interview participants and participating countries from each thematic group.

Sub-taks expert group	Number of participants	Number of countries
Sub-task 1 group: Power systems integration	20	6
Sub-task 2 group: ICT and data	8	5
Sub-task 3 group: Transactions and markets	21	8
Sub-task 4 group: Social and economic value	17	9
Sub-task 5 group: Policy and regulation	16	9

While some of the terms (P2P, CSC and TE) had definitions created within specific disciplinary and geographic domains (and these were included in the corpus terminology review), there were widely differing uses of the terms between disciplines and countries. Given the nascent nature of the terms (P2P, CSC and TE) and the differing use in practice across disciplinary and geographic domains, a primarily socioterminological approach of mapping how the terms are used in practice was adopted looking for shared characteristics between terms as a constructive step on the road to shared understanding across disciplines. The steps followed in this paper conform to the European Commission's Working Party on Terminology and Documentation Recommendations for Terminology Work (2nd edition) 2003. These guidelines recommend a combination of analysis of specialist documents and the development of terms in conjunction with expert opinions.

2.1. Expert interviews

Expert interviews aim to elicit specific knowledge from individuals with specialised knowledge on the topic [17]. Expert interviews were used for the purpose of identifying a set of characteristics that distinguish P2P/TE/CSC models from traditional energy systems.

Experts from a wide range of disciplines and sectors in 13 countries across four continents were interviewed: Europe, North America, South America and Australia. Expert interviewees were recruited from GO-P2P. Five expert group interviews were conducted in the summer of 2020, each focusing on a different aspect of the class of models encompassing P2P/TE/CSC. This enabled a cross-disciplinary perspective on understanding these models. Interviewees consisted of academics, regulators, and industry stakeholders. Table 1 outlines the sub-tasks corresponding to GO-P2P's working groups.

Prior to the interview, all participants were asked to submit their top five key characteristics they believed distinguish these models from traditional energy systems from the perspective of their group:

> *"Please list a minimum of five key common characteristics of Peer-to-Peer Energy Trading (P2P), Community/Collective Self-Consumption (CSC) and Transactive Energy (TE) models from the perspective of sub-task 3 (transactions and markets). From this perspective, what are the main characteristics that are shared by P2P, TE and CSC models?*
>
> *By characteristic, we mean a feature or quality belonging typically to a person, place, or thing and serving to identify them. Please focus on attributes that describe P2P/CSC/TE models using single words or phrases rather than full sentences".*

During the interview, participants were asked to openly comment on the list of submitted characteristics and add additional characteristics, before voting on the top defining characteristics of this class of

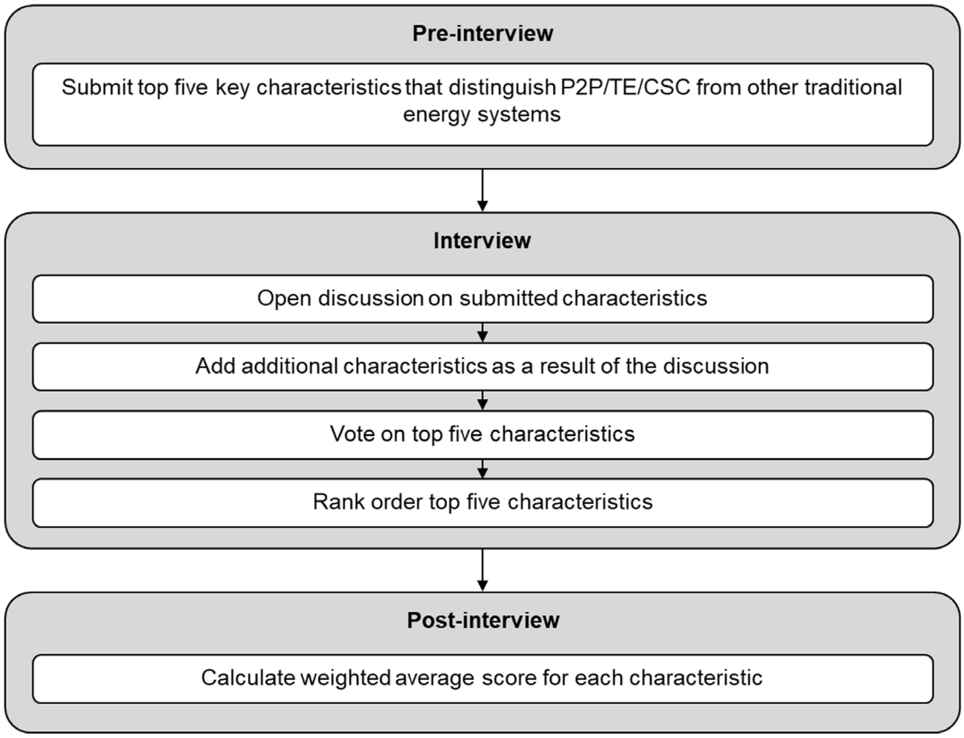

Fig. 1. Overview of expert interview analysis method.

model from their group's perspective. A semi-structured discussion was held around the outcome of the vote until consensus was reached on the top defining characteristics. After the interview, participants were asked to individually rank order the top characteristics. A weighted average score for each characteristic was calculated, with respondents' first choice having a weight of eight, second choice having a weight of seven, and so on. Characteristics were coded thematically by a single independent coder. Fig. 1 shows an overview of the steps taken before, during, and after the interview. Please see supplementary material for the full interview guide.

Group (as opposed to individual) interviews allowed a wider range of views to be collected, as well as identifying points of consensus and disagreement within the field.

As there was a risk that country or context specific terms could dominate the expert interviews, the interviews focused on the defining characteristics of the *class of models*, rather than specific terms. Another challenge posed by interviewing stakeholders with an interest in this field is the possibility of introducing bias, for example stakeholders suggesting defining characteristics aligned with their own projects.

2.2. Literature review

The literature review counters the challenge of potential bias in the interviews by offering insight into how the terms P2P, TE and CSC are each used in a sample of academic and industry literature. It also allows us to understand how these terms are used in the field, outside of an interview situation where participants are aware that they are being observed.

Data took the form of definitions and characteristics of P2P, TE and CSC models found in a sample of academic and non-academic (i.e. industry and policy) literature. Literature was identified through a combination of systematic and targeted approaches. First, a pre-registered, systematic search was run using combinations of the terms *peer-to-peer/peer-to-peer energy trading, community/collective self-consumption and transactive energy + 'defin*'*. The search was conducted in August 2020 and the full search protocol can be found in the supplementary material or at https://osf.io/bnfmp/.

During screening, it was noted that the academic literature identified by this protocol was dominated by modelling papers focused on understanding the effect of different market parameters. To achieve more equal representation of literature across disciplines and ensure that key papers had not been missed out, an additional call for literature specifically discussing definitions or characteristics of P2P/TE/CSC models was issued to the GO-P2P community. This resulted in additional papers being added (both academic and non-academic). Duplicates were removed and papers were screened using criteria applied in the systematic review. Given that much of the work in this field is more amenable to study by simulation rather than more resource-intensive field trials, a frequentist sampling of the literature was not undertaken. This allowed us to focus on characteristics that are present or absent for each model rather than replicating the state of evolution of the field. Combining the literature review with the expert interviews also helps overcome this limitation of the literature review, as the interviews represent a wide range of disciplinary perspectives.

Out of all papers, 78 academic and 55 non-academic papers contained either definitions or characteristics of P2P, TE, or CSC and were included in the final analysis. Fig. 2 shows the number of papers identified at each stage of the screening process.

The literature was restricted to articles only published in English, meaning that some contexts outside of English-speaking countries may have been missed. However, the wide geographical representation provided by interviewees mitigates this limitation.

Finally, data from the expert interviews and the literature review was triangulated, drawing from both sources to critically reflect on how the terms P2P, TE, and CSC are being used among experts and in literature and understand its implications for the energy sector.

3. Defining the class of models: Expert interview results

The following sections present the results of the expert interviews aimed at understanding which characteristics distinguish P2P, TE and CSC models from traditional energy systems. Fig. 3 shows an overview of the characteristics identified by each thematic group as the top, defining characteristics of this class of models.

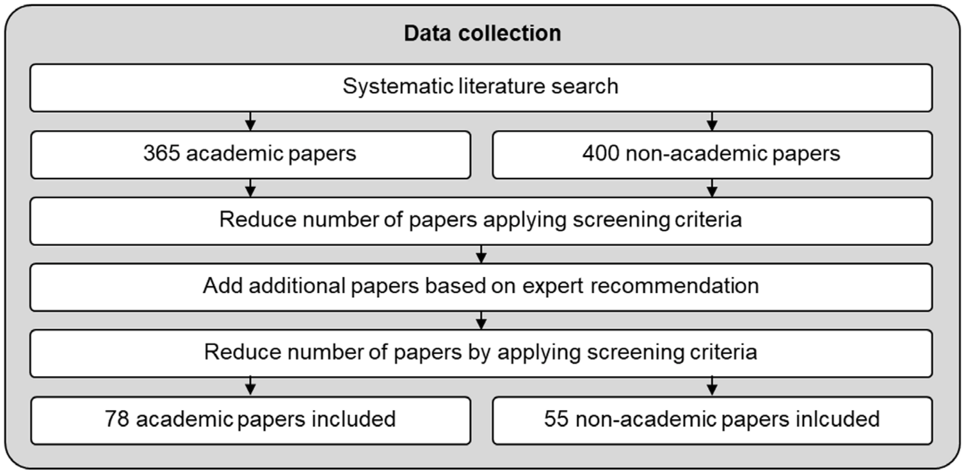

Fig. 2. Overview of literature review data collection.

In the group focused on Power systems integration, eight defining characteristics of the class of models encompassing P2P, TE and CSC were identified. According to this group, for a system to be considered as belonging to this class of models, it must: support integration of local generation; be decentralised; use local distribution networks (i.e. low voltage (LV) networks); include a smart energy interface and control mechanism; participants must have smart meters; the system must support the integration of renewable energy; promote energy self-consumption; and operate autonomously. During the discussion, the importance of locality as a defining characteristic of these models was highlighted, although participants noted that the community-orientated nature of these models had been missed in the characteristics put forward. Interview participants were of the view that the level of complexity involved in P2P/TE/CSC energy trading is too great to allow participants to make manual transactions and that consumers are unable to make informed decisions about aspects such as active/reactive power. For these reasons, it was felt that an autonomous system would be required.

The ICT and data group identified nine defining characteristics of P2P/TE/CSC models. These were: advanced metering infrastructure; interoperable data that can be shared with and interpreted by all actors in the system; components of the system have application programming interfaces allowing for the exchange of data and control commands between system components; distributed infrastructure for data management; consumer interfaces that allow participants to express trading preferences; devices have a traceable identity; independent agents at device level; compliance with local data protection laws; and ICT having the capacity to deal with current and future frequency, diversity and volume of data. Notably, many of the characteristics described by this group focus more on practical elements required for the system to operate, rather than features that necessarily distinguish the system from traditional energy systems. The topic of interoperability played a key role both in terms of data structures and devices. Similarly to the Power Systems integration group, this group highlighted the expectation that trading would be handled by an automated system, in line with preferences set by participants. During the interview, participants highlighted the need to distinguish between features that would be required for these systems to operate and those required for them to scale. Interviewees also highlighted the distinction between interoperable and standardised, noting that interoperability of devices and data within the system would be required in order for them to function, whereas standardisation would be important for scaling.

In the Transactions and Markets group, seven defining characteristics were identified: prosumer-centric markets; active participation from end-users; the promotion of local generation and consumption; decentralised markets and generation assets; a market designed to capture value from flexibility and balancing; the ability to trade commodities i.e. energy or services; and for markets to be enabled by digitalisation and the integration of devices and communication. The role of prosumers in the market was an important theme during the interview, with some debate about the extent to which end-users could be expected to make 'active' decisions in order for the market to be considered as belonging to the P2P/TE/CSC class of models. There was general consensus that users would likely have the option to be active participants, by setting preferences for trading and optimisation of their energy use and generation, but much of the trading would be done on their behalf through an automated system. Interviewees also highlighted that many energy markets feature digitalisation, meaning that this characteristic does not necessarily distinguish these models from traditional energy systems, but it would be essential for P2P/TE/CSC markets to be feasible. Participants also felt it was important to highlight that decentralised energy markets might involve trading energy commodities other than electricity, such as heat or grid services and flexibility.

In the interview focusing on social and economic value, eight defining characteristics of P2P/TE/CSC models were identified: the promotion of local production and consumption of energy/electricity; the inclusion (implicitly or explicitly) of both monetary and non-monetary returns; a clear demonstration of the exercise of rights; open and equitable access through a bottom-up market design; markets simultaneously located in socially different spheres such as the home, within the community, and the wider market; inclusion of market-determined pricing, including dynamic pricing; systems that generate, modify and reinforce social values; and the involvement of a minimum of two social units (i.e. an energy-giver and energy-receiver). In addition to characteristics relating to local generation and consumption that were also noted by previous expert groups, interviewees in the social and economic value group highlighted the importance of social relationships within these models. Interviewees noted that these relationships can take place in different spheres, from the home, to the community, to the wider market. There was discussion about how, unlike traditional energy systems, P2P/TE/CSC models have the potential to create new forms of social value and relations, but also to change exisiting social dynamics. Financial incentives for participation were mentioned, as was the need for market-driven pricing, but the importance of non-financial aspects was also strongly endorsed by interviewees as a factor that distinguishes these models from traditional energy systems. The rights of participants (e.g. the right to ownership, right to consumption) also featured in the discussions. In order for these social, economic, and legal features to be realised, interviewees noted that there needs to be at least two uniquely identifiable agents to engage in an energy transaction. This could be a household or a device. Interviewees also

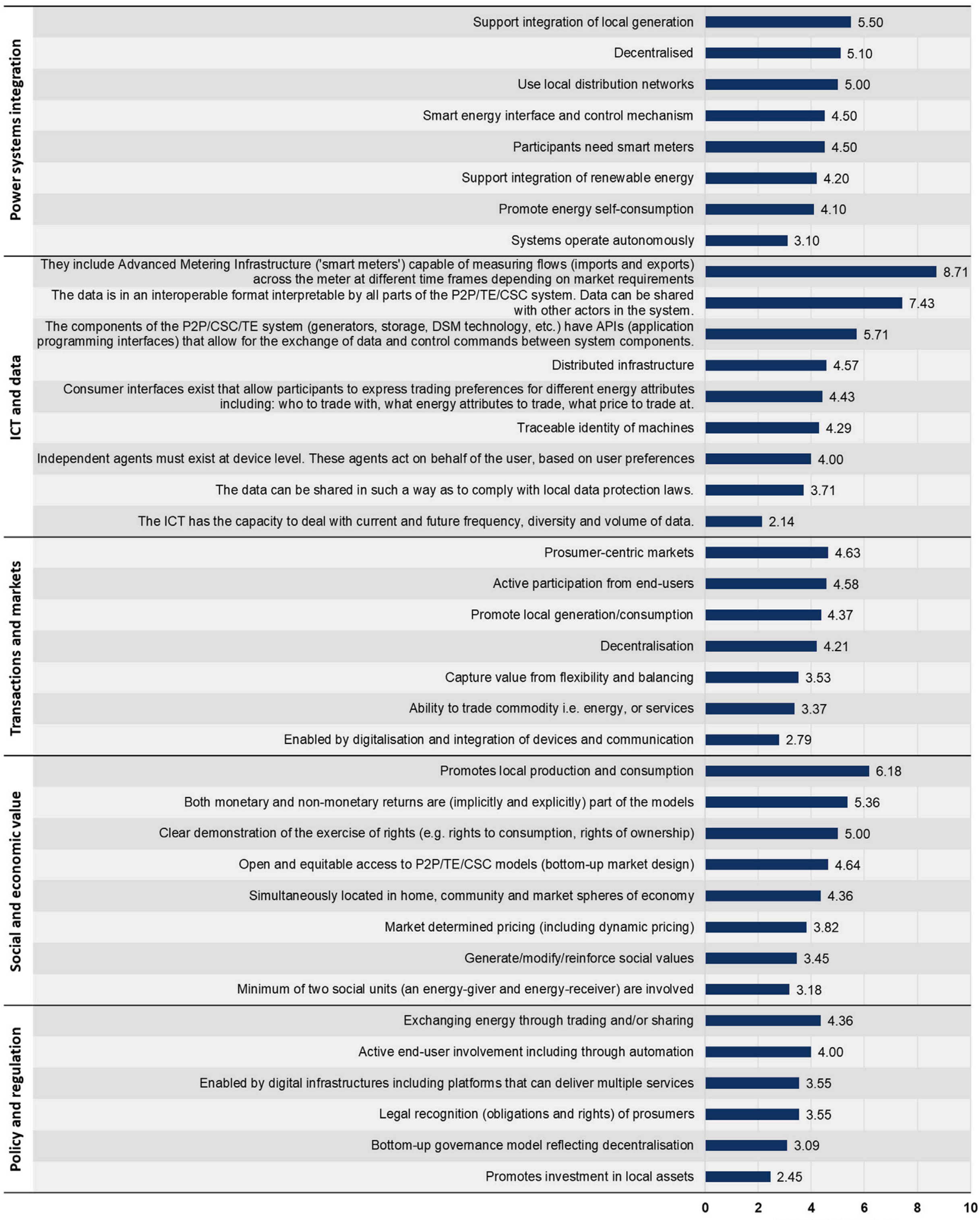

Fig. 3. Top defining characteristics by sub-task expert group.

pointed to the importance of context, noting that in the Global South, energy access and fuel poverty is a much more important aim of these systems than decarbonisation or grid flexibility.

The final group, policy and regulation, identified six defining characteristics of P2P/TE/CSC models: energy exchanged through trading and/or sharing; active end-user participation, including through automation; platforms enabled by digital infrastructure, including platforms that can deliver multiple services (e.g. trading of energy or flexibility); legal recognition (i.e. obligations and rights) of prosumers; a bottom-up governance model reflecting decentralisation; and the promotion of investment in local assets (e.g. storage). Whilst many of the characteristics listed by this group overlap with previous expert groups, their discussion of them focused on the regulatory and legal perspective. Interviewees felt it was important to make a distinction between sharing and trading electricity and other energy services, noting that, although energy sharing is mentioned many times in the EU Directive RED II, it is not properly defined. Interviewees also noted that the closest equivalent to P2P in the current market is sleeving arrangements. There was also discussion of automation as a way of reducing the effort required to engage with the system. Interviewees felt that being an 'active' participant can include a one-off setting of preferences, which are then automated. Much emphasis was also placed on the rights of prosumers and consumers within the system: interviewees stated that from a regulatory standpoint, P2P/TE/CSC models involve the recognition of the principle of prosumer responsibility - i.e. the prosumer will be legally responsible for his or her actions or inactions from a supply, distribution and generation perspective. From a settlement point of view, these models all assume that the prosumer will ultimately bear legal responsibility for his or her balance position. Overall, interviewees felt that, from a regulatory perspective, there are strong distinctions between these models and it is difficult to define them as a class.

To summarise, the findings across all expert interviews indicate common themes of automation as necessary to enable consumer use of these models, as well as the importance of values such as locality and community. Expert discussions also highlight the inclusion of all types of (geographic) scale of models, even solely virtual P2P schemes, which encompass both trading that aligns generation and demand in space and time and trading that only aligns generation and demand in time. However, there were also some contradictions between characteristics identified in each group interview. These common themes and contradictions are discussed further in Section 5 and triangulated with findings from the literature review.

4. Differentiation of models: Literature review findings

The previous section of the paper outlined the characteristics that define the class of models described as P2P/TE/CSC according to experts in the field. The second part of this paper focuses on identifying the characteristics which set P2P, TE and CSC models apart from one another and those that they have in common.

4.1. Qualitative content analysis

During the search process as outlined in Section 2.2, it was found that many of the papers that met our search criteria used several other terms interchangeably with P2P/TE/CSC. As the aim of this paper is to reflect how researchers and practitioners refer to these systems in practice, it was included these additional terms in the data extraction process. Given that these terms are co-evolving and that there is no globally accepted definition, it was deemed important to capture the diversity of terms used in this conceptual space.

Once the additional samples of papers had been identified, definitions, characteristics, and terms were extracted from the literature. Statements describing features that the system is, has, enables, or does were coded as *Characteristics*. Labels given to the system described were coded as *Terms*.

This data was coded in NVivo, a qualitative data analysis software, using a combination of deductive and inductive qualitative content analysis [17]. Two coders each independently coded half of the sample using inductive qualitative content analysis to identify unique, distinct characteristics. Results were then refined through discussion between coders. Each coder then used the agreed list of terms and characteristics to deductively check each other's half of the sample until agreement was reached between coders. Characteristics were initially coded as specifically as possible, and later grouped into broader themes for ease of presentation in the paper. Each identified characteristic was also coded against the term used in the document describing it.

In interpreting these results, it is important to note that a characteristic being coded against a term only means that it was observed at least once in our snapshot of literature.

4.2. Analysis of terms

After data cleaning, a final list of 95 characteristics and 36 terms were identified that were associated with the terms P2P, TE and CSC. Please see Fig. 4 and supplementary material for a full list of characteristics and terms.

In order to understand which broader terms are being used in the literature to refer to P2P, TE and CSC models and how similar they are to one another with regards to the number of characteristics they share, a similarity matrix was calculated using the similarity index (SI). The similarity matrix can be seen in Fig. 4.

Each term was treated as a vector with a series of 1s and 0s indicating whether or not each characteristic was present for that term (without an indication of how many times). Eq. (1) outlines the similarity index calculated. The resulting matrix indicating the similarity of terms can be seen in Fig. 4.

$$SI = \frac{|Term_H \cap Term_V|}{|Term_H|} \quad (1)$$

The value of SI in each cell of the matrix indicates how many characteristics the vertical terms $Term_V$ share with the horizontal terms $Term_H$. For example, the term *P2P energy sharing* has a total of 25 characteristics of which it shares 20 characteristics with the term *P2P energy trading*. This would mean the SI between *P2P energy sharing* and *P2P energy trading* is 0.8.

The terms *P2P energy trading* and *transactive energy* were the terms most frequently appearing in the definitions analysed and are often used interchangeably, sharing many characteristics. The similarity index between TE and P2P is higher than vice versa. This indicates that *transactive energy* is defined more broadly, while *P2P energy trading* provides more detailed characteristics. Alongside P2P energy trading several other terms have been used describing the same or a similar concept including *P2P energy sharing*, *P2P electricity supply* and *P2P energy market*. The terms *Transactive control* and *Transactive energy systems* were often used synonymous with TE or would describe sub-concepts of it. Other terms such as *Renewable Energy Community* and *Citizen Energy Community* were predominantly used in non-academic literature. Both of these terms are defined in the revised EU Renewable Energy Directive (RED II) [9]. Similarly, the term *Collective self-consumption* can be attributed to the EU regulatory framework [18].

In order to reduce the noise caused by the constantly evolving nature of the field and establish the key prevailing concept, terms expressing the same or similar fundamental concept were merged together. Ideally speaking, terms should share 100% of their characteristics in order to be considered as the same concept and, therefore, merged into one. This would require an SI of 1. However, given this situation, there are likely to be characteristics associated with a specific context. For this reason, a more lenient threshold of 80% and merged terms that had an SI ≥ 0.8 were used. Terms which met this

	Behind the meter trading	Citizen energy community	Collective self consumption	Community based market	Community energy	Community microgrid	Connected community	Decentralised energy market	Decentralised P2P trading	District power models	Energy Community	Energy sharing	Federated power plant	Flexibility markets	Flexibility platform	Local collective use	Local energy community	Local energy market	P2P electricity trading	P2P energy market	P2P energy sharing	P2P energy trading	P2P energy trading network	P2P microgrid	P2P power trade	P2P supply	P2P trading of renewable energy	P2P transactive models	Peer-to-community platforms	Prosumer community group	Renewable energy community	Transactive control	Transactive energy	Transactive energy systems	Virtual Power Plant	Virtual self consumption	Number of characteristics
Behind the meter trading	1	0.08	0	0	0.09	0.08	0	0	0.18	0	0.1	0.11	0	0	0.33	0	0	0.1	0.07	0.08	0.08	0.05	0.07	0.29	0.1	0	0	0.1	0.15	0.11	0.06	0.25	0.04	0.1	0.13	0	3
Citizen energy community	0.67	1	0.31	0.33	0.65	0.35	0.33	0.33	0.46	0.5	0.67	0.22	0.6	0.25	0.5	0.33	0.8	0.38	0.28	0.23	0.32	0.2	0.29	0.43	0.2	0	0.17	0.2	0.54	0.56	0.94	0.25	0.18	0.1	0.5	1	24
Collective self consumption	0	0.21	1	0	0.22	0.23	0.11	0.17	0	0.83	0.14	0	0	0	0	0.67	0.4	0.14	0.14	0.12	0.12	0.14	0.29	0	0.2	0	0.17	0.2	0.31	0.11	0.13	0	0.08	0.1	0.13	0	16
Community based market	0	0.08	0	1	0.09	0.15	0	0.17	0.09	0	0.05	0	0.2	0.25	0	0	0	0.1	0.07	0.04	0.12	0.07	0	0	0.1	0	0	0.1	0	0.22	0.13	0	0.06	0	0.13	0	6
Community energy	0.67	0.63	0.31	0.33	1	0.39	0.33	0.25	0.36	0.5	0.62	0.33	0.6	0.25	0.33	0.17	0.8	0.33	0.28	0.27	0.32	0.22	0.5	0.29	0.1	0.33	0.17	0.2	0.46	0.56	0.69	0.5	0.22	0.3	0.13	0	23
Community microgrid	0.67	0.38	0.38	0.67	0.44	1	0.33	0.25	0.27	0.67	0.33	0.22	0.4	0.5	0.33	0.5	0.6	0.52	0.35	0.31	0.36	0.31	0.36	0.14	0.3	0.33	0	0.2	0.46	0.56	0.38	0.25	0.28	0.4	0.5	0	26
Connected community	0	0.13	0.06	0	0.13	0.12	1	0.17	0.09	0.17	0.14	0.56	0.4	0.25	0.17	0	0.4	0.24	0.17	0.15	0.24	0.15	0.36	0.14	0.2	0	0.17	0.1	0.23	0.22	0.13	0.25	0.16	0.1	0	0	9
Decentralised energy market	0	0.17	0.13	0.33	0.13	0.12	0.22	1	0.27	0.17	0.1	0.22	0.6	0	0.17	0	0.2	0.24	0.24	0.31	0.24	0.17	0.29	0.14	0.2	0	0	0.3	0.15	0.22	0.25	0.25	0.2	0	0.25	0	12
Decentralised P2P trading	0.67	0.21	0	0.17	0.17	0.12	0.11	0.25	1	0	0.1	0.22	0.4	0.25	0.5	0	0	0.24	0.28	0.27	0.24	0.17	0.21	0.57	0.3	0.17	0.5	0.2	0.39	0.11	0.25	0.5	0.22	0.1	0.25	1	11
District power models	0	0.13	0.31	0	0.13	0.15	0.11	0.08	0	1	0.05	0.11	0.2	0	0	0.5	0.2	0.14	0.07	0.08	0.12	0.03	0.21	0	0	0	0	0	0.23	0.11	0.06	0	0.02	0	0	0	6
Energy Community	0.67	0.58	0.19	0.17	0.57	0.27	0.33	0.17	0.18	0.17	1	0.22	0.2	0.25	0.33	0.17	0.8	0.24	0.21	0.19	0.24	0.19	0.14	0.29	0.1	0.17	0.17	0.2	0.39	0.67	0.63	0.25	0.16	0.3	0.13	0	21
Energy sharing	0.33	0.08	0	0	0.13	0.08	0.56	0.17	0.18	0.17	0.1	1	0.4	0.25	0.17	0	0.2	0.24	0.21	0.23	0.24	0.15	0.36	0.43	0.1	0.17	0.33	0.1	0.31	0.11	0.06	0.25	0.16	0.1	0	0	9
Federated power plant	0	0.13	0	0.17	0.13	0.08	0.22	0.25	0.18	0.17	0.05	0.22	1	0.25	0.17	0	0.2	0.19	0.14	0.15	0.08	0.07	0.14	0	0	0	0	0.1	0.15	0.11	0.13	0	0.1	0.1	0.13	1	5
Flexibility markets	0	0.04	0	0.17	0.04	0.08	0.11	0	0.09	0	0.05	0.11	0.2	1	0.17	0.17	0	0.1	0.07	0.04	0	0.03	0.07	0	0.1	0	0	0	0	0	0.06	0	0.06	0.1	0.13	0	4
Flexibility platform	0.67	0.13	0	0	0.09	0.08	0.11	0.08	0.27	0	0.1	0.11	0.2	0.25	1	0	0	0.14	0.1	0.12	0.08	0.09	0.07	0.14	0.2	0	0.17	0.2	0.08	0.11	0.13	0.5	0.1	0.1	0.38	0	6
Local collective use	0	0.08	0.25	0	0.04	0.12	0	0	0	0.5	0.05	0	0	0.25	0	1	0	0.1	0.03	0.04	0	0.03	0.07	0	0	0.17	0	0	0	0	0.06	0	0	0	0	0	6
Local energy community	0	0.17	0.13	0	0.17	0.12	0.22	0.08	0	0.17	0.19	0.11	0.2	0	0	0	1	0.1	0.03	0.08	0.08	0.03	0.07	0	0	0	0	0	0.08	0.11	0.19	0	0.04	0	0	0	5
Local energy market	0.67	0.33	0.19	0.33	0.3	0.42	0.56	0.42	0.46	0.5	0.24	0.56	0.8	0.5	0.5	0.33	0.4	1	0.38	0.5	0.56	0.32	0.5	0.71	0.5	0.17	0	0.4	0.39	0.33	0.31	0.25	0.33	0.4	0.5	0	21
P2P electricity trading	0.67	0.33	0.25	0.33	0.35	0.39	0.56	0.58	0.73	0.33	0.29	0.67	0.8	0.5	0.5	0.17	0.2	0.52	1	0.54	0.48	0.44	0.64	0.71	0.5	0.5	0.33	0.7	0.69	0.44	0.31	0.5	0.49	0.5	0.5	1	29
P2P energy market	0.67	0.25	0.19	0.17	0.3	0.31	0.44	0.67	0.64	0.33	0.24	0.67	0.8	0.25	0.5	0.17	0.4	0.62	0.48	1	0.44	0.37	0.43	0.71	0.4	0.33	0.83	0.7	0.39	0.33	0.31	0.75	0.39	0.5	0.38	0	26
P2P energy sharing	0.67	0.33	0.19	0.5	0.35	0.35	0.67	0.5	0.55	0.5	0.29	0.67	0.4	0	0.33	0	0.4	0.67	0.41	0.42	1	0.34	0.57	0.71	0.5	0.33	0.5	0.4	0.54	0.44	0.44	0.5	0.41	0.4	0.38	0	25
P2P energy trading	1	0.5	0.5	0.67	0.57	0.69	1	0.83	0.91	0.33	0.52	1	0.8	0.5	0.83	0.33	0.4	0.91	0.9	0.85	0.8	1	0.86	0.86	0.9	1	0.83	0.9	0.69	0.89	0.56	1	0.71	0.7	0.88	0	59
P2P energy trading network	0.33	0.17	0.25	0	0.3	0.19	0.56	0.33	0.27	0.5	0.1	0.56	0.4	0.25	0.17	0.17	0.2	0.33	0.31	0.23	0.32	0.2	1	0.29	0.4	0	0.17	0.3	0.39	0.11	0.19	0.5	0.2	0.1	0.13	0	14
P2P microgrid	0.67	0.13	0	0	0.09	0.04	0.11	0.08	0.36	0	0.1	0.33	0	0	0.17	0	0	0.24	0.17	0.19	0.2	0.1	0.14	1	0.2	0.17	0.17	0.2	0.31	0.11	0.13	0.25	0.12	0.2	0.13	0	7
P2P power trade	0.33	0.08	0.13	0.17	0.04	0.12	0.22	0.17	0.27	0	0.05	0.11	0	0.25	0.33	0	0	0.24	0.17	0.15	0.2	0.15	0.29	0.29	1	0	0.17	0.4	0.15	0.11	0.13	0.25	0.18	0.1	0.13	0	10
P2P supply	0	0	0	0	0.09	0.08	0	0	0.09	0	0.05	0.11	0	0	0	0.17	0	0.05	0.1	0.08	0.08	0.1	0	0.14	0	1	0.17	0.1	0.15	0	0	0	0.08	0.1	0	0	6
P2P trading of renewable energy	0	0.04	0.06	0	0.04	0	0.11	0	0.27	0	0.05	0.22	0	0	0.17	0	0	0	0.07	0.19	0.12	0.09	0.07	0.14	0.1	0.17	1	0.1	0.15	0	0.13	0.25	0.1	0	0	0	6
P2P transactive models	0.33	0.08	0.13	0.17	0.09	0.08	0.11	0.25	0.18	0	0.1	0.11	0.2	0	0.33	0	0	0.19	0.24	0.27	0.16	0.15	0.21	0.29	0.4	0.17	0.17	1	0.08	0.11	0.13	0.5	0.16	0.2	0.13	0	10
Peer-to-community platforms	0.67	0.29	0.25	0	0.26	0.23	0.33	0.17	0.46	0.5	0.24	0.44	0.4	0	0.17	0	0.2	0.24	0.31	0.19	0.28	0.15	0.36	0.57	0.2	0.33	0.33	0.1	1	0.22	0.25	0.25	0.2	0.1	0	1	13
Prosumer community group	0.33	0.21	0.06	0.33	0.22	0.19	0.22	0.17	0.09	0.17	0.29	0.11	0.2	0	0.17	0	0.2	0.14	0.14	0.12	0.16	0.14	0.07	0.14	0.1	0	0	0.1	0.15	1	0.31	0.25	0.06	0.1	0.13	0	9
Renewable energy community	0.33	0.63	0.13	0.33	0.48	0.23	0.22	0.33	0.36	0.17	0.48	0.11	0.4	0.25	0.33	0.17	0.6	0.24	0.17	0.19	0.28	0.15	0.21	0.29	0.2	0	0.33	0.2	0.31	0.56	1	0.25	0.16	0.1	0.38	0	16
Transactive control	0.33	0.04	0	0	0.09	0.04	0.11	0.08	0.18	0	0.05	0.11	0	0	0.33	0	0	0.05	0.07	0.12	0.08	0.07	0.14	0.14	0.1	0	0.17	0.2	0.08	0.11	0.06	1	0.08	0.1	0	0	4
Transactive energy	0.67	0.38	0.25	0.5	0.48	0.54	0.89	0.83	1	0.17	0.38	0.89	1	0.75	0.83	0	0.4	0.81	0.86	0.77	0.84	0.61	0.71	0.86	0.9	0.67	0.83	0.8	0.77	0.33	0.5	1	1	0.9	0.63	1	51
Transactive energy systems	0.33	0.04	0.06	0	0.13	0.15	0.11	0	0.09	0	0.14	0.11	0.2	0.25	0.17	0	0	0.19	0.17	0.19	0.16	0.12	0.07	0.29	0.1	0.17	0	0.2	0.08	0.11	0.06	0.25	0.18	1	0.13	0	10
Virtual Power Plant	0.33	0.17	0.06	0.17	0.04	0.15	0	0.17	0.18	0	0.05	0	0.2	0.25	0.5	0	0	0.19	0.14	0.12	0.12	0.12	0.07	0.14	0.1	0	0	0.1	0	0.11	0.19	0	0.1	0.1	1	0	8
Virtual self consumption	0	0.04	0	0	0	0	0	0	0.09	0	0	0	0.2	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0.08	0	0	0	0.02	0	0	1	1

Fig. 4. Term similarity matrix.

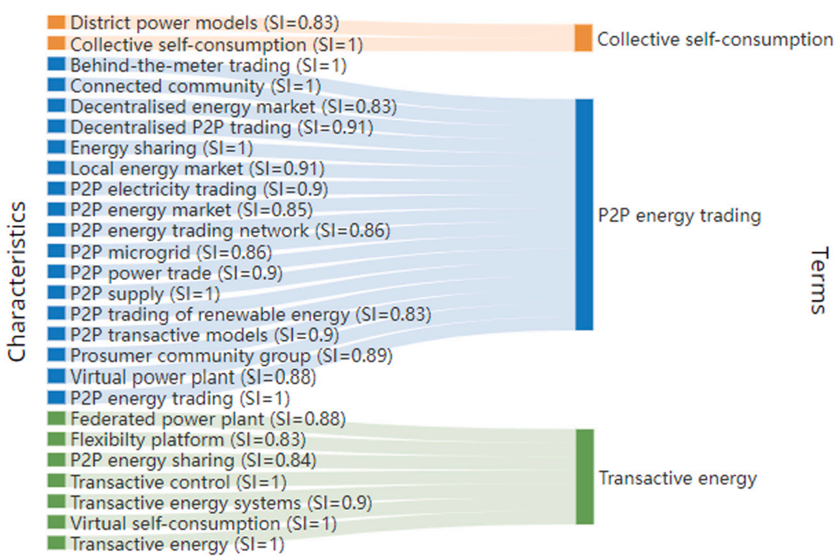

Fig. 5. Terms merged based on number of shared characteristics with similarity index (SI) indicated in brackets.

condition could be considered sufficiently similar to be merged. Using this approach P2P, TE and CSC emerged as the three dominant terms with all other terms being either a sub-concept of one of the three terms or a separate unique concept. The merging of terms took place by only considering the number of characteristics shared to account for the interchangeable and inconsistent use of terms. This should not mean that the term or concept can be considered a standalone term in certain disciplines. The threshold value used influences the results of this analysis and is an important limitation to note.

A total of 26 terms were merged into the three dominant terms. There were 10 terms which did not have enough shared characteristics to be merged with P2P, TE, or CSC and were not considered in the further analysis (see Fig. 5).

An overview of the steps taken can be seen in Fig. 6.

4.3. Analysis of characteristics

In this section, the third research aim is addressed: to understand which characteristics are associated with P2P, TE, and CSC respectively, and where the similarities and differences between them lie.

After removing characteristics of the unique terms that were not shared with the merged terms, a total of 80 characteristics were identified across all terms. It is important to note that if a characteristic has not been coded as part of a particular term, this does not necessarily mean that this characteristic cannot be associated with the term, but

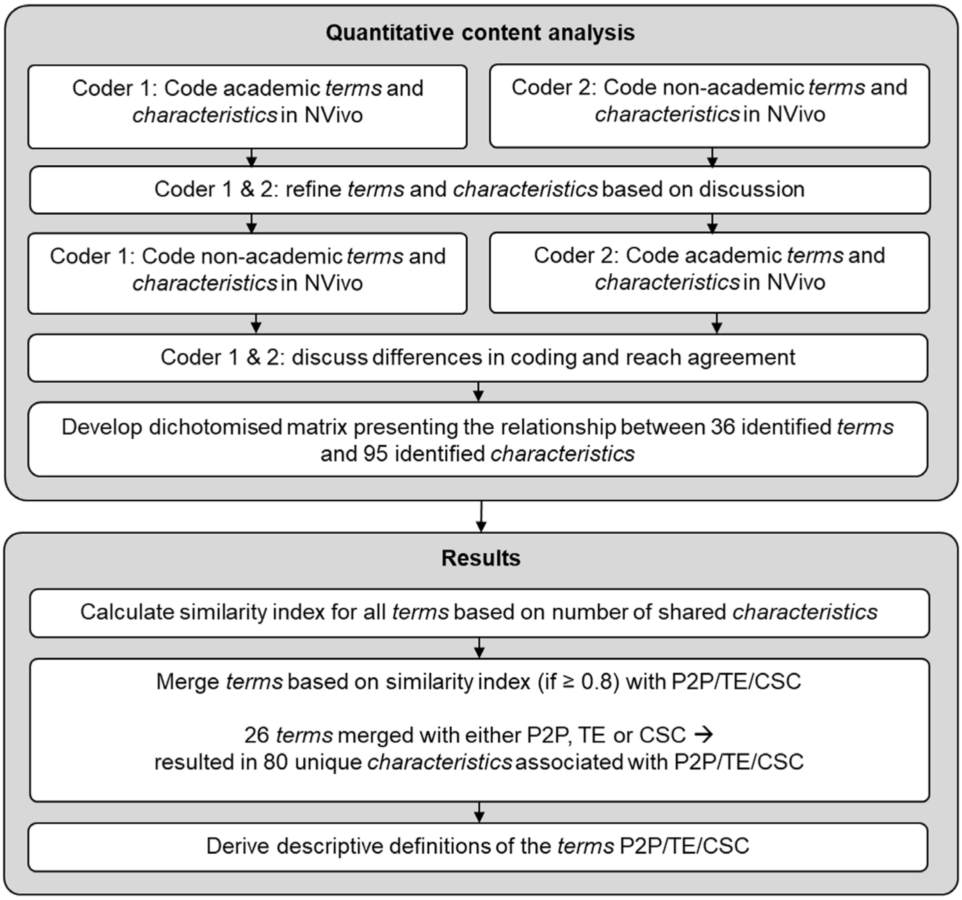

Fig. 6. Overview of quantitative content analysis and results.

rather that the characteristic was not observed in the literature reviewed that mentioned this term. This is an important limitation of the analysis which, by necessity of resource constraints and the immature state of the field, focused on a snapshot of literature.

Discussion of characteristics associated with the three main terms has been organised according to seven main themes. These themes were implemented to allow for clearer visualisations and identification of similarities and differences between terms across key dimensions of these models and have no order of importance. An overview of each characteristic and its associate reference can be viewed in Table A.9.

4.3.1. *Market or system aims and incentives*

Table 2 shows characteristics associated with each model under the theme of market or system aims and incentives; a coloured square indicates that at least one source in the literature sampled associated this characteristic with this model.

Table 2
Characteristics explicitly ■ (dark) and not explicitly ■ (light) associated with terms related to market or system aims and incentives.

Characteristic	P2P	TE	CSC
Balancing of demand and supply	dark	dark	dark
Self sufficiency	dark	dark	light
Reduce energy loss	dark	light	dark
Promote or include RES generation	dark	dark	light
Promote or include DER generation	dark	dark	light
Participants have greater control over preferences	dark	dark	light
Optimisation of energy behaviour to benefit system	dark	dark	light
Management of grid constraints	dark	dark	light
Flexibility trading	dark	dark	light
Energy democracy	dark	dark	light
Economic incentives for participation	dark	dark	light
Aggregation of participant energy loads	dark	dark	light
Social benefits	dark	light	light
Shared benefits across the community	light	light	dark
Identification of origin of energy supply	dark	light	light
Environmental benefits	dark	light	light
Community as focal point for engagement	light	light	dark

All three models shared the aim of *balancing of demand and supply*. For TE, this characteristic features prominently in the Gridwise Architecture Council definition: “TE refers to economic and control mechanisms that allow the dynamic balance of supply and demand across the entire electrical infrastructure, using value as a key operational parameter” [19]. This definition appears to have influenced other descriptions of TE as similar descriptions are found in [20–23]. P2P and CSC both share the additional goal of *reducing energy loss*.

Characteristics excluded by CSC, but shared by TE and P2P tend to relate to benefit the overall system (e.g. *management of grid constraints; promote Renewable Energy Sources (RES) and DER generation; optimisation of energy behaviour to benefit system; aggregation of participant loads; flexibility trading*) [e.g 2,3,20,23–40].

Incentives for participation in TE and P2P models include *economic incentives*. Notably, TE seems to frame economic value as an incentive, whereas P2P presents it as an outcome. For TE, economic incentives are often mentioned in connection to incentivising grid optimisation behaviour [19] and by descriptions of “demand-side parties optimis[ing] their behaviour in response to economic signals, to minimise overall energy cost” [37]. For P2P, economic incentives are mentioned both in terms of unspecified economic benefits and more specific benefits for prosumers such as earning revenues and reducing electricity costs [41] or for system operators in terms of lowering operational costs [20].

Both P2P and TE also refer to *self-sufficiency*. For both models this is described as reduced dependence on the grid [41,42], whereas

Table 3
Characteristics explicitly ■ and not explicitly ■ associated with terms related to participant type and scale.

Characteristic	P2P	TE	CSC
Consumers with photovoltaic (PV) solar systems	explicitly	explicitly	explicitly
small-scale participants	explicitly	explicitly	not explicitly
Prosumers	explicitly	explicitly	not explicitly
Equal in size market participants	explicitly	explicitly	not explicitly
Diverse types of energy generators and consumers	explicitly	explicitly	not explicitly
Individuals or at communities	explicitly	not explicitly	not explicitly
Groups of participants	explicitly	not explicitly	not explicitly
Commercial power consumers	explicitly	not explicitly	not explicitly

descriptions of P2P also explicitly mention reduced reliance on a central supplier and increased self-determination and autarky for participants [43]. This is perhaps reflective of the more individualistic and decentralised nature of P2P, discussed in Section 5.2.1.

Both P2P and TE also focus on giving participants more power and control over their energy consumption through *energy democracy* and *greater control over preferences*, empowering individuals to participate in energy markets. P2P takes this a step further, mentioning that P2P transactions could be traced back to their origin [44]. This associates P2P with a move away from purely financial or system-focused benefits and into alternative value propositions, such as social and environmental benefits. This is less explicit for TE: the Gridwise Architecture Council [19] mentions "a wide array of societal benefits" but does not state the nature of these benefits or who they are delivered for. Similarly, [23] mention that TE can bring "social dimensions" to the grid, but does not specify whether these are social benefits.

Characteristics unique to CSC involve *shared benefits across the community* and *community as a focal point for engagement*. For example, [45] describes community microgrids as aiming to "maximiz[e] the social welfare of the community" in a manner that ensures that the solution for each member is at a minimum not worse than an individual outcome. [46] also makes reference to "shared identity or desire for strong, self-reliant communities". This suggests that there is a more explicit focus on community-oriented, social value propositions for this model.

4.3.2. Participant type and scale

Table 3 shows that the presence of *consumers with PV solar systems* is common across all models. This is the only type of participant specifically mentioned for CSC models; however, unlike P2P and TE, descriptions of CSC focus on shared access. For example, [47] describes CSC as allowing "a group of actors [to consume] electricity from a shared PV system" and [48] characterises building-scale CSC as allowing "several electricity consumers located in one single building [to] benefit from the electricity produced by a PV system installed on the same building".

Papers discussing TE and P2P both mention the ability for *diverse types of energy generators and consumers* to participate, including the broad category of *prosumers*. For P2P, definitions categorised under this characteristic vary: [49] summarises participants in P2P as consisting of "a variety of players, with equal access to a common resource and goal of sharing it through a wealth of cooperating infrastructures", whereas [25] emphasises the "diversity of the generation [...] and demand profiles of different customers". [32] notes that a "peer can be a single person or an authority" whilst [20] mentions the ability for P2P to be "employed at higher levels for energy trading between microgrids, energy communities, or VPPs [Virtual Power Plants]". These broad, and at times contradictory, definitions indicate that P2P is used to refer to a wide range of systems. Although *diverse types of energy generators and consumers* is also coded for TE, the focus here is more on the heterogeneity of participants, in terms of their type [24,50] and size [51].

Some sources for P2P highlight that participants should be *small-scale* and that trading takes place between participants that are *equal in size* [e.g. 31,32,52–54]. In line with the market aim of increased self-sufficiency, several sources for P2P also highlight that participants can be entities previously excluded from the energy market, now able to trade energy without reliance on the retail market, centralised suppliers, or large companies [20,32,41,52,55,56]. Although *small-scale participants* and *equal in size* are also coded for TE, this is only mentioned by [32], which describes TE as providing an "opportunity for small and mid-sized energy consumers or producers to exchange energy".

P2P is the only model to mention that commercial consumers can also be included [57]. This indicates that P2P places greater emphasis on the decentralised nature of transactions than necessarily on the type of participants involved. In this vein, [38] mentions that groups of participants can take part in P2P and contract as a coalition with a retail supplier.

4.3.3. Participant interactions

As shown in Table 4, texts discussing CSC did not specify how participants within the system might interact with one another. Texts describing TE and P2P mention both the possibility of *autonomous communication between participants* [29,39]. However, both models also highlight the possibility for *active end user participation*. For TE, this is largely characterised in terms of allowing control over their energy transactions and a means of procuring value for the grid [20,22]. For P2P, the theme of active end user participation is also described in terms of active negotiation of energy procurement [58,59], but also highlights consumer empowerment in the form of "greater freedom to engage in transactions with partners of their choice" [54] as well as having "more choice over where they purchase energy from" [60]. This highlights the importance of non-financial value for P2P.

Under TE and P2P, market participants are considered to be *independent and self-interested decision makers* [41,44,61]. Notably, [62] refer to actors in both P2P and TE as behaving in a rational and individualistic manner in order to maximise their own profit. Conversely, [49] mentions the possibility of P2P actors having *shared energy trading goals*: "One can see it as a variety of players, with equal access to a common resource and goal of sharing it through a wealth of cooperating infrastructures, which is opposite to the traditional economic principle represented by players with individual goals". This particular definition might be more aligned with what might typically be considered to be a CSC project, demonstrating the wide range of projects that have been labelled as P2P and the inconsistencies between the uses of these labels.

P2P also places emphasis on the freedom of trading and participation. [63], describes P2P as "the most challenging market design arrangement; consumers and prosumers have the possibility to freely trade with a central part or, in its purest form, between each other". Relatedly, [64] emphasise that participants should be able to be added or removed from a P2P network without adverse effects on network stability.

4.3.4. Market or system design

Characteristics related to the design of the market as seen in Table 5 are limited to P2P and TE models. For both P2P and TE market coordination mechanisms range from centralised to distributed to decentralised. *Centralised coordination and management* in TE is only mentioned once and is associated with P2P energy sharing [30]. Generally speaking, TE puts a stronger focus on decentralised and distributed management for better privacy [65] and system scalability [39]. In P2P the key aim of a decentralised or distributed system is to avoid a central intermediary party [20,40,61,66,67].

However, [28] highlights that P2P energy trading might "rely on some degree of centralised communication and control, rather than being strictly based on P2P negotiation and autonomous decision making". A similar view is supported by [35] in the case of VPPs. [68] considers both possibilities, using centralised controller to manage a market or relying on decentralised technologies to avoid a centralised

Table 4
Characteristics explicitly ■ and not explicitly □ associated with terms related to participant interactions.

Characteristic	P2P	TE	CSC
Participants are independent and self interested decision makers	■	■	□
Autonomous communication between participants	■	■	□
Active end-user participation	■	■	□
Participants trade freely with one another	■	□	□
Participants have shared energy trading goals	■	□	□
Participants can be added or removed without affecting network	■	□	□

Table 5
Characteristics explicitly ■ and not explicitly □ associated with terms related to market or system design.

Characteristic	P2P	TE	CSC
Two-sides market	■	■	□
Smart IT platform	■	■	□
Market rules and mechanisms	■	■	□
Market-based price signals	■	■	□
Interaction with third parties and wholesale market	■	■	□
Dynamic pricing	■	■	□
Distributed market coordination and management	■	■	□
Decentralised market coordination an management	■	■	□
Competitive market structure and pricing	■	■	□
Centralised market coordination and management	■	■	□
Autonomous grid control	■	■	□
Time-of-use tariffs	■	□	□
Sub-market within traditional market	■	□	□
Nodal or local grid pricing	■	□	□
Grid as supplier of last resort	■	□	□
Coordination and management of smart devices	□	■	□
Concept based on sharing economy	■	□	□

Table 6
Characteristics explicitly ■ and not explicitly □ associated with terms related to market or system scale.

Characteristic	P2P	TE	CSC
Local energy trading or market (geographic region)	■	■	■
Bound by LV-distribution network	■	■	■
Virtual energy trading (no geographical restrictions)	■	■	□
Operate in grid-connected mode	■	■	□
Bound by local community	■	■	□
Bound by distribution network	■	■	□
Operates on various levels of the grid	□	■	□
Operates on public electricity grid	□	□	■
Operates on private electricity grid	□	□	■
Operates in island mode	■	□	□
Connected at distribution grid level	□	■	□
Bound by building or block	□	□	■

party. Centralised market management is associated with roles such as "community manager" [64], "licensed suppliers" [68] or "centralised controller" [30]. It can be observed that the more decentralised a market becomes, the stronger the focus on autonomous trading is in the case of P2P [1,67,69] and *autonomous grid control* in the case of TE [27,39,42].

The aspect of trading plays an important role in P2P and TE highlighted by characteristics such as *market rules and mechanisms* with a *competitive market structure and pricing* using e.g. "negotiations" [2] or "optimisation" [42]. Further, a market can incentivise different types of participant behaviour: "The members may work either in a collaborative or a competitive manner" [64]. P2P and TE make use of *market-based price signals*, to react to grid constraints and balance demand and supply of energy [2,19,20,35,38,42,52].

Pricing mechanisms used by both include *dynamic pricing* [20,41, 43,70], while P2P explicitly mentions *time-of-use tariffs* [71] and *nodal and local grid pricing* as a subcategory [72]. As outlined by [41]: "As an independent decision maker, a prosumer may intend to sell his or her surplus energy at different rates to different buyers within the network", highlighting the role of diverse pricing schemes in P2P to incentivise certain load behaviour or include consumer preferences.

P2P can operate as a *sub market within a traditional market* [73] and requires the *grid as the supplier of last resort*. While [74] mention that P2P could effectively replace the current role of the energy supplier, [75] state that P2P could contribute to a better balance of demand and supply alongside the services delivered by the supplier. Demand not satisfied by own generation could be met by the supplier [38,62]. This is in line with the characteristics mentioned under Section 4.3.1 describing the aims and incentives of the market or system.

Finally, TE markets have a stronger focus on *coordination and management of smart devices*, mainly customer devices [24,39,76], while P2P, being derived from the *concept of sharing economy* [25,75] focuses more on the prosumers and the relationships between them [1].

4.3.5. Market or system scale

Table 6 shows characteristics related to market and system scale. The characteristics mainly focus on specifying whether a market or system is bound by the topology of the grid or locality of the community and to what extent. A frequent mention were the two opposing characteristics that describe whether a system is designed as a *local energy trading or market (geographic region)* or through *virtual energy trading (no geographical restrictions)*. Both P2P and TE explicitly consider both forms of market design. As highlighted in the context of TE: "it can be applied within a localised area, e.g., microgrid, or be utilised to manage the whole power system" [77]. Specifically the balancing of energy can be conducted "virtually" to benefit participants of these markets [75]. [47] describe this form of virtual energy trading as "virtual self-consumption, where generation and consumption of PV happens at the same time but in differing locations".

For TE, it is highlighted that the system can *operate across various levels of the grid* [19,21,24,78,79], starting at the local prosumer level and going up to the whole energy system, including the wholesale market. The levels of market operation strongly correlate with the participant types and scales involved in the market as described in Section 4.3.2. In summary, TE is less restricted by a specific level of the electricity grid compared to P2P or CSC.

CSC is the only model that explicitly limits the scale of the market operation for example by a building or block [48]. CSC also specifies that the sharing of electricity can be conducted on a *private or public electricity grid* [47,80]. Whether a market runs on a public or private electricity grid can impact the governance model of the market and ultimately the type of concept in use.

All three terms consider a certain degree of locality by restricting the market or trading place to be *bound by the LV-distribution network*. Other characteristics expressing a similar concept mentioned for P2P and TE included the market being *bound by a local community* [34,40] or *bound by the distribution network* [22,65]. Finally, *islanded operation* rather than grid-connected operation was considered in the case of P2P [64]. However, this was mentioned in association with the concept of microgrids [44,49,66], which was merged with P2P during the analysis of terms in Section 4.2.

In general it can be said that the concept of locality plays an important role in all three terms, not least to integrate DER efficiently into the energy system. However, boundaries of locality are case-dependent and can be considered in the context of a geographical region, the topology of the grid, or physical structure.

Table 7
Characteristics explicitly ■ and not explicitly ■ associated with terms related to market or system transactions and settlement.

Characteristic	P2P	TE	CSC
Real-time trading	Explicit	Explicit	Explicit
DLT for energy transaction and settlement	Explicit	Explicit	Explicit
Automatic execution and settlement	Explicit	Explicit	Explicit
Use of virtual or real currencies	Explicit	Not explicit	Explicit
Trading of renewable energy	Explicit	Explicit	Not explicit
Physically delivered energy	Explicit	Explicit	Not explicit
Multi-directional exchange of energy and value	Explicit	Explicit	Not explicit
Manual energy trading	Explicit	Not explicit	Explicit
Frequent transactions	Explicit	Explicit	Not explicit
Energy transactions without intermediary	Explicit	Explicit	Not explicit
Energy transactions through intermediary	Explicit	Explicit	Not explicit
Contracting for energy services offered and delivered	Explicit	Explicit	Not explicit
Bi-directional energy flows	Explicit	Explicit	Not explicit
Transactions of reactive power	Not explicit	Explicit	Not explicit
Transactions of real power	Not explicit	Explicit	Not explicit
Trading of different classes of energy	Explicit	Not explicit	Not explicit
Multilateral bidding transactions	Explicit	Not explicit	Not explicit
Forward energy transactions	Not explicit	Explicit	Not explicit
Deferred energy transactions	Not explicit	Explicit	Not explicit

4.3.6. *Market transactions and settlement*

Table 7 shows characteristics related to market transactions and settlements. Characteristics are predominantly represented by P2P and TE models. All three market models mention *automatic execution and settlement* of transactions as a key characteristic, while P2P and CSC also consider *manual energy trading*. In the words of [35], P2P "enables prosumers to buy and sell energy directly - manually or via automation - with a high degree of autonomy". In both concepts, the degree of automation can vary [35,81].

To conduct transactions in the market, all three models mention *DLT for energy trading and management* [26,35,81,82]. It is mainly used to establish trust between the parties involved and allow for a more decentralised and automated management of the market, e.g. through the use of smart contracts [40,44]. Amongst others, the use of this technology can also determine whether energy transactions happen *with or without an intermediary*. Avoiding intermediaries in some cases refers to making central electricity suppliers redundant [38,83,84] while in other instances it refers to specifically the removal of any "centralised supervisor" or mediator [49,64]. In these cases, the presence of bi-lateral or *multilateral bidding transactions* is necessary [41,67,71,85].

When intermediaries are considered, it is often in the form of a "central marketplace" [86,87] or an "aggregator" [18,29] that facilitates transactions between parties. The integration of a centralised third party is frequently mentioned in the context of the RED II definition [18,29,82].

A shared aim across all models, regardless of whether they conduct transactions with or without an intermediary is to avoid or reduce the dominance of and dependence on the traditional utility company when exchanging energy [56].

P2P and TE were also associated with *trading of renewable energy*, with TE further segregating the type of energy traded. In TE, both *real and reactive power* can be transacted [34]. P2P puts a stronger focus on participants' preferences and includes *trading of different classes of energy* [49,58,88]. Papers describe how participants can trade different classes of energy, with attributes going beyond financial considerations [44]. For example, those interested in locality could select the provenance of their electricity [71], environmentally conscious prosumers can buy renewable energy, and philanthropic prosumers could supply subsidised energy to low-income households [28].

For both terms, the *physical delivery of energy* plays a key role [54,70] including through *bi-directional energy flows* [24,62,89]. As described by [54] the physical delivery of energy "impose[s] physical limits on the electricity trade". Market designs that consider the physical flow of energy would therefore have a stronger focus on locality as discussed in Section 4.3.5. Such market designs would ultimately be linked with the *multi-directional exchange of energy and value* [27,68,81,90].

The time scale of the transactions was mainly highlighted by TE, which allows for *forward and deferred energy transactions* [26,70] meaning transactions can be settled prior or after their occurrence. All three models offer *real-time trading* in particular to "facilitate a sustainable and reliable generation and consumption of energy within the community" [91] and respond to short term needs of the grid [34,39,59].

Table 8
Characteristics explicitly ■ and not explicitly ■ associated with terms related to governance.

Characteristic	P2P	TE	CSC
Shared ownership of generation assets	Explicit	Not explicit	Explicit
Non-traditional business model	Explicit	Explicit	Not explicit
Assets owned by customers and third parties	Explicit	Explicit	Not explicit
Participants not selling energy professionally	Explicit	Not explicit	Not explicit
Owners have control over devices	Not explicit	Explicit	Not explicit
Extension of existing business models	Explicit	Not explicit	Not explicit
Equal responsibility and rights for all participants	Explicit	Not explicit	Not explicit
Community operates as legal entity	Explicit	Not explicit	Not explicit

4.3.7. *Governance and policy*

Table 8 shows that the only characteristic of governance unique to TE is the explicit mention of *owners having control of their own devices* [39].

Another characteristic of TE also shared by P2P includes *assets owned by customers and third parties*. [82] highlights that DER assets are individually owned and installed behind-the-meter in P2P networks, and [21] notes that TE systems extend to all levels of the grid, including customer-owned and third-party assets.

The literature also discusses the disruptive nature of P2P and CSC as a *non-traditional business model*, in terms of allowing smaller suppliers to compete with large, traditional suppliers [61]. [74] goes so far as to say that "theoretically, P2P-supply could make the role of the traditional Supplier, i.e. a centralised profit-driven market party, redundant in the long term". By contrast, [54] describes P2P as an *extension of existing business models*, with the platform being operated by existing energy market players. This highlights a gap between the radical ambition of P2P and its practical implementation. Similarly, [92] describes TE as "liberating the data that will transform energy markets, and rewarding consumers with better energy services that come from utilising the existing grid and adding new infrastructure where it is needed most". Whilst texts describing P2P speak of the potential redundancy of traditional suppliers, representing a shift in power away from traditional entities and towards individuals, those describing TE appear to view this model as complementing existing markets rather than replacing them. This generally aligns with the characteristics discussed in Section 4.3.4.

P2P also mentions *shared ownership of generation assets*, a characteristic shared with CSC. [49] describes how, in P2P, in addition to individual trading, "a community can also be formed by prosumers who want to collaborate, or in terms of operational energy management". For CSC this is much more focal and participants are typically mentioned in terms of groups of consumers [47,48,80]. For CSC only, it is explicitly mentioned that the *community operates as a legal entity*.

Notably, P2P also highlights that all participants have *equal rights and responsibilities*, emphasising its focus on egalitarianism. Additionally, [54] highlights that a transaction can only be qualified as P2P when it is undertaken by two *non-professional actors*.

5. Discussion

5.1. Common themes

Several common themes emerged across all disciplinary perspectives in the expert group interviews and in the sample of literature reviewed.

5.1.1. Digitalisation and automation

The first common theme across all sub-task expert group interviews and the literature is that of automation. Most expert groups highlighted automation as an important characteristic of P2P/TE/CSC models to enable consumer participation. Similarly, in the literature, P2P and TE were associated with autonomous communication and grid control between participants.

Groups focused on the technical aspect of LEMs argued that automation is necessary since consumers cannot be expected to manually manage transactions in practice. This should not contradict the presence of active participation as highlighted by groups 3 and 5. Automation could reduce the effort required by consumers to be active e.g. with intervention only at the beginning to set parameters according to group 5 on policy and regulation. Different interpretations of end-user participation are also borne out in the literature. There is a distinction between 'participation' in the sense of allowing end-users to express their preferences without the need for continued engagement, and a more active form of participation involving behavioural change and active engagement with the energy system and energy trading platforms. Papers discussing TE tended to speak about end-user engagement in terms of the former, whereas papers discussing P2P tended to include both forms of participation.

On the broader topic of digitalisation, there was consensus across several expert groups that smart meters in particular are key to the functioning of P2P/TE/CSC models. Furthermore, groups 2 and 4 felt it essential that data collected should be in an interoperable format so that it can be shared with actors across the market and aggregated. In the literature, smart IT platforms were mentioned in papers discussing P2P and TE. For all three models, the use of DLTs for energy transactions and management was mentioned in the literature, while not specifically discussed in the expert interviews.

5.1.2. Values

Almost all expert groups agreed that P2P/TE/CSC models are characterised by their promotion and support of the local generation and consumption of energy or local assets. Similarly, in the literature, papers discussing P2P and TE both mentioned the promotion or inclusion of renewable and DER assets. Energy trading at the local geographic region is mentioned in the literature for all models. Locality is therefore a crucial value driving these systems.

According to expert interviews, actors in the system should be able to trade and/or share energy and related services. This can be in cash, in kind or in intangible payment. The concept of trading different energy classes was also mentioned in the literature on P2P. Group 3 on market design raised the point that P2P/TE/CSC systems can include a diverse resource portfolio, e.g. markets including power, heating, cooling, transport (via electric vehicles) and both thermal and electrical storage. Similarly, literature on P2P and TE mentioned the possibility for diverse types of energy generators or consumers to be included in the system.

As for consumers' motives for participating, in the expert interviews, there was consensus between group 3 on market design and 4 on social and economic value that both monetary and non-monetary values drive P2P/TE/CSC systems. These are framed as either individual or community-based (i.e. shared) benefits. This is broadly aligned with the literature reviewed, although these incentives appear to differ for P2P, TE, and CSC models. Economic incentives for participation were mentioned in papers discussing P2P and TE, whereas social benefits for individuals were mostly associated with P2P, and shared benefits across communities were a core feature of CSC.

5.1.3. Scale and governance

Several expert groups pointed to the fact that in most P2P/TE/CSC systems, energy is not being traded in a 'physical' sense as the origin of the electricity cannot be tracked once it is injected onto the grid, rendering the exercise of trading as depending on what can be netted. Therefore, models centred around the virtual trading of energy and distributed networks are also considered to be P2P/TE/CSC according to groups 1 on power systems and 3 on markets and transactions. In contrast, the reviewed literature highlighted that the trading of energy could be geographically restricted or traded virtually, whereby the term "physically" as used by the interviewed experts could refer to locally restricted markets.

Group 5 on policy and regulation also highlighted that there should be no size requirement. Many of the current pilots are being carried out within a microgrid, private wire or behind-the-meter setting. These should also be included under the class of models encompassing P2P/TE/CSC. This is strongly supported by the characteristics associated with CSC in the literature, where energy trading can be restricted to one building or block.

Furthermore, there was consensus across several expert groups that in order for these business models to become viable, they must be able to use the local or public distribution network. Pilots should be designed to function at a larger scale, in order to be integrated into the main energy grid. The latter implies that individuals or entities involved in pilots would have to offer services and take on obligations traditionally applicable to a licensed utility, such as balancing responsibilities, customer billing, and upholding data privacy rules- or partner up with a utility to do this. In the literature this feature was associated with the term TE, which focuses on providing grid services and engaging in energy trading across various levels of the grid. The consideration of grid services in the market activities played a key role in the market design characteristics for P2P and TE.

The legal recognition of trading entities, such as energy prosumers and communities, is therefore crucial. There needs to be a clear demonstration of the rights (e.g. right of ownership, right to consumption) and obligations of these new market entrants according to expert groups 4 and 5. This will require the setting up of verification processes and adaptation of the licensing framework. Government policies to encourage flexible behaviour by consumers will also be necessary as highlighted by group 5 on policy and regulation. While this was also described in the characteristics identified as part of the literature review, detailed information on verification processes and licensing frameworks is yet to be established. Nevertheless, CSC in particular put a strong focus on the shared ownership of generation assets and the operation as a legal entity.

When it came to market governance, in the interviews, group 5 on policy and regulation in particular but also groups 3 and 4 agreed that P2P/TE/CSC models should include a democratic and bottom-up governance model reflecting the decentralised nature of these systems. Stakeholders can input into and arrive at a consensus on how the market is designed or structured. There was a similar discussion in the literature on the values of energy democracy, particularly associated with P2P, as well as shared ownership of generation assets in P2P and CSC models. Papers discussing P2P additionally mentioned the possibility of participants being defined at either the individual or community level.

5.1.4. Market design

The topic of market design was discussed in all expert interviews. For group 3, the top priority was for these systems to be prosumer-centric markets. Group 4 also highlighted the importance of open and equitable access to P2P/TE/CSC models, which must be designed in a user-centred manner, as well as include residential and commercial participants that are 'relatively small' in size (e.g. not a nuclear power station). Furthermore, markets need to be designed to allow for individual or communal ownership of distributed assets according to group 5.

Equally, communal assets were a key characteristic of CSC in the literature review. Social benefits and shared benefits were associated with P2P and CSC in the literature, respectively. While for CSC it was generally assumed that small-scale consumers with PV installations are involved, P2P and TE papers highlighted that the key targeted market participants should be equal in size in support of the group 4 experts' statement.

Group 4 on social and economic value placed particular importance on the personal dimension of market interactions. Trading needs to take place between two points, individual participants or a group of participants, which are identifiable and visible on the system. Additionally, participants in groups 1 and 3 suggested that transactions between participants could be direct, i.e. without any involvement of intermediaries. In contrast to this, in the literature, both trading with and without intermediaries was discussed for the concepts of P2P and TE.

Regarding market parameters, groups 1, 3 and 4 agreed that dynamic pricing is a key component of P2P/TE/CSC models. However, it was argued that dynamic pricing may only be one example of real-time trading, opening the way for other types of pricing mechanisms. The crucial point here is that the pricing system should be determined by the participants according to group 4. A local central market coordinator may also be necessary according to the experts. Group 4 raised the valuable point that non-market pricing should also be included, as observed in the Global South. Similarly, in the literature review various forms of real-time or dynamic pricing structures were discussed that could incentives a certain behaviour of the market participants. However, these flexible pricing strategies were mainly associated with the concepts of P2P and TE. The trading aspect was not discussed in detail in literature with regard to CSC, which might support the comment made by group 4 about non-market pricing-focused concepts.

In summary, there was broad agreement between the defining characteristics of P2P, TE and CSC as a whole identified in the expert interviews and in the literature review, albeit with different emphases given by particular models and disciplinary perspectives. The next section focuses on results obtained from the literature review discussing differences identified between P2P, TE, and CSC to establish an overview of the three models individually.

5.2. Comparison between models

Given the results and insights gained from Sections 3 and 4, the following sections aim to describe the terms P2P, TE and CSC. Rather than providing rigid definitions, the key characteristics identified in the expert interview and literature reviews are drawn upon, and key features or present boundary conditions that enable differentiation between the term are described.

5.2.1. P2P energy trading

Peer-to-peer energy trading is the most richly described term in the literature, with the greatest number of characteristics. Consequently, the projects described as P2P have the broadest range of characteristics. In terms of the system aims and incentives, P2P encompasses system-orientated benefits as well as social and environmental benefits, and increased control over preferences and self-sufficiency for participants. However, it does not mention community-focused aims. P2P can encompass a diverse range of participants, from individuals to groups to commercial consumers. Also emphasised is that participants are small-scale, non-professional, and equal in size. P2P is also distinguished from the other two models in that it places emphasis on the freedom of participants to come and go without affecting the network, and that participants are able to act as self-interested decision makers or with shared trading goals. Similarly, assets can be owned by individuals or shared. P2P can be operated in a central, distributed or decentralised way. Transactions can take place with or without an intermediary. The trading aspect is key to P2P with a particular focus on competitive markets. They can operate within a sub-market alongside traditional markets i.e. fall under the operation responsibility of distribution system operators. P2P has been mentioned to be bound by a geographic area or consist of virtual energy trading. P2P can be an extension of existing models as well as a disruptive business model, and places emphasis on all peers having equal rights and responsibilities.

> Based on this analysis, P2P is defined according to the following characteristics: it is a sub-market that can operate alongside traditional energy markets. Individuals can trade energy within a community, which can be bound locally or encompass virtual trading across a large geographical region. Participants can be heterogeneous in type but are typically small-scale and equal in size. Although P2P markets are set up to encourage competitive behaviour, with economic incentives and prosumers having individual trading preferences and goals, the overall market aim generally pertains to social, environmental, and energy democratisation benefits.

5.2.2. Transactive energy

Most of the aims and incentives associated with TE pertain to system benefits and optimising the integration of RES and DER generation. Benefits for participants are associated with self-sufficiency, democratisation of energy, control over preferences, and economic incentives. Participants act as individual, self-interested decision makers, again pointing towards a more individualistic incentive structure, albeit constrained by the grid. This is also reflected in the ownership of assets by consumers and third parties and in that owners have control over their own devices. In TE, participants can communicate autonomously, or be active participants. Similarly to P2P, TE highlights that participants can be diverse but should be small-scale and equal in size. TE markets can be operated in a central, decentralised or distributed way. They are dependent on an intelligent platform and use different forms of pricing mechanisms to trade energy. Both trading that aligns generation and demand in space and time and trading that only aligns generation and demand in time can be traded across various levels of the grid. TE also emphasises the non-traditional business model.

> TE is therefore characterised as a non-traditional business model that allows energy end-users to have greater control over their energy trading preferences. It typically provides economic incentives for participants to trade energy in a manner that supports electricity grid balancing. The system can operate across various levels of the electricity grid. Similar to P2P, participants are typically small-scale and equal in size. Different types of energy can be traded. The primary value of TE tends to pertain to systems such as grid stability and reliability while supporting the increasing installation of DER and RES.

5.2.3. Collective/community self-consumption

CSC is the only model to put explicit focus on community-oriented aims and the sharing of benefits across the community. This is reflected in the shared ownership of generation assets. It also mentions benefits such as balancing demand and supply and reducing energy loss, but does not explicitly mention the system and economic aims and incentives highlighted by P2P and TE. The only types of participants explicitly mentioned are consumers with PV. Characteristics describing the market are limited. CSC usually operates within specific topological restrictive areas, i.e. the LV grid or a building or block. Energy trading can be conducted manually or through automatic execution and settlement. As CSC is the only model with a legal definition, it is also

Table A.9
Overview of characteristics and associated references.

Characteristic type	P2P	TE	CSC
Market or system aims and incentives			
Balancing of demand and supply	[3,28,43,52,73,75]	[10,19–24,34,42,57,65,90,93–101]	[81]
Self-sufficiency	[41,43,74]	[42]	
Reduce energy loss	[30,81,102]		[81]
Promote or include RES generation	[3,18,29–31,33,43,57,60,91,103]	[24,83,104]	
Promote or include DER generation	[20,25,30,35,38,41,82,105,106]	[20,24,34,39,42,65,104]	
Participants have greater control over preferences	[24,28,38,41,44,49,58,60,61,69,71,72,84,88,107]	[20,28,30]	
Optimisation of energy behaviour to benefit system	[30,40,64,87]	[24,30,37,90,92,108]	
Management of grid constraints	[3,20,25,28,30,31,44,71,73,109]	[2,10,20,23,24,26–28,34,65,93,94,110]	
Flexibility trading	[3,25,31,72,88,111]	[24,70,79]	
Energy democracy	[54,84]	[39,104]	
Economic incentive for participation	[20,24,25,28,41,43,44,54,62,64,71,72,102,106,107,112,113]	[2,10,19,20,23,24,27,30,34,37,39,42,50,57,65,73,76,77,83,90,93–101,108,110,111,114,115]	
Aggregation of participant energy loads	[20,28,35,69,111,116]	[35]	
Social benefits	[28,102,113]		
Shared benefits across the community	–	–	[82]
Identification of origin of energy supply	[28,44,71,72,74,107]	–	–
Environmental benefits	[28,102]	–	–
Community as focal point for engagement	–	–	[18,82]
Participant types and scales			
Consumers with PV solar systems	[112]	[115]	[47,48]
Small-scale participants	[20,22,24,31,36,52,53,55,56,58,72,82,91,105,106,111,112,117]	[24,26,51,65,83,104,115,118]	–
Prosumers	[1,22,24,25,28,31,44,54,56,62,64,68,85,87,91,117,119]	[22,24,30,42,51,73,78,83,87,104]	–
Equal in size market participants	[20,41,54,106]	[65]	–
Diverse types of energy generators and consumers	[20,25,35,38,49,52,55,58,105,111]	[24,28,35,50,51,76,83,110,120]	–
Individuals or communities	[75]	–	–
Groups of participants	[38,102]	–	–
Commercial power consumers	[57]	–	–
Participant interactions			
Participants are independent and self-interested consumers	[41,44,49,61,62]	[24,30]	–
Autonomous communication between participants	[29,85]	[39]	–
Active end user participation	[20,24,43,54,58,60,84,102,113]	[20,22–24,30,51,93]	–
Participants trade freely with one another	[63,106]	–	–
Participants have shared energy trading goals	[102]	–	–
Participants can be added or removed without affecting network	[64]	–	–
Market or system design			
Two-sided market	[20]	[20]	–
Smart IT platform	[30,31,33,38,42–44,60–62,64,68,71,72,103,106,121]	[2,24,30,39,42,50,51,77,93,102,104,110,111]	–
Market rules and mechanisms	[38,44,52,64]	[2,30,42]	–
Market based price signals	[20,35,43,68]	[10,19,20,35,65,108]	–
Interaction with third parties and wholesale market	[24,54,74,75]	[20,24,78]	–
Dynamic pricing	[41,43,71]	[19,20,70,114]	–
Distributed market coordination and management	[122,123]	[83,104,114,118]	–
Decentralised market coordination and management	[1,20,24,40,61,64,67,69,103,112]	[20,24,34,39,64,65,94]	–
Competitive market structure and pricing	[38,44,62,106,122]	[24,51,83]	–
Centralised market coordination and management	[28,35,68,102]	[30]	–
Autonomous grid control	[1]	[27,39,42]	–
Time of use tariffs	[71]	–	–
Sub market within traditional market	[20,73,75]	–	–
Nodal or local grid pricing	[72]	–	–
Grid as supplier of last resort	[38,52,62,74,75]	–	–
Coordination and management of smart devices	–	[24,39,76]	–
Concept based on sharing economy	[25,75]	–	–

(continued on next page)

Table A.9 (*continued*).

Market system and scale			
Local energy trading or market (geographic region)	[24,28,30,31,33,40,42,52,60,62,67,84,84,87,103,105,112,113,119,121,124,125]	[24,26,28,30,51,77]	[47,80]
Bound by LV-distribution network	[31]	[115]	[47,126,127]
Virtual energy trading (no geographical restrictions)	[56]	[24,28,47,77,79,83]	–
Operate in grid-connected mode	[24,30,52,64,86]	[34,104]	–
Bound by local community	[40]	[30,34]	–
Bound by distribution network	[22]	[24,65,70,101]	–
Operates on various levels of the grid	–	[10,19,21,24,34,57,78,79,90,93–100,114]	–
Operate on public electricity grid	–	–	[47,80]
Operate on private electricity grid	–	–	[47,80]
Operate in island-mode	[64]	–	–
Connected at distribution grid level	–	[70,115]	–
Bound by building or block	–	–	[48]
Market transactions and settlement			
Real-time trading	[40,41,56,72,81,91]	[24,26,34,39,70]	[81]
DLT for energy transaction and management	[35,40,44,68,81,82,106,124]	[26,118]	[81]
Automatic executions and settlements	[18,29,35,69,72,81,82,106]	[2,24,26,39]	[81]
Use of virtual or real currencies	[44,81]	–	[81]
Trading of renewable energy	[25,30,41–44,53,62,69,103,125]	[42]	–
Physically delivered energy	[54]	[70]	–
Multi-directional exchange of energy and value	[20,24,41,67,68,72,81,88,119,121,125]	[27,90,128]	–
Manual energy trading	[35,81]	–	[81]
Frequent transactions	[42,86]	[42,90]	–
Energy transactions without intermediary	[3,18,22,24,25,28,29,35,38,40–42,49,55–57,61,63,69,71,74,82,85,86,107,111,121]	[42,64,83,110,115]	–
Energy transactions through intermediary	[18,29,63,82,86,87]	[30]	–
Contracting for energy services offered and delivered	[1,18,29,54,81,82]	[64,70,79,90,111]	–
Bi-directional energy flows	[62,85]	[21,24,39,73,89]	–
Transactions of reactive power	–	[34]	–
Transactions of real power	–	[34]	–
Trading of different classes of energy	[38,44,49,58,88]	–	–
Multilateral bidding transactions	[40,49,88]	–	–
Forward energy transactions	–	[70]	–
Deferred energy transactions	–	[26]	–
Governance and policy			
Shared ownership of generation assets	[49,64,91,112]	–	[47,48,80,126]
Non-traditional business model	[61,74]	[92,110,115]	–
Assets owned by consumers and third parties	[82]	[21]	–
Participants not selling energy professionally	[54]	–	–
Owners have control over devices	–	[39]	–
Extension of existing business models	[54,75]	–	–
Equal responsibility and rights for all parties	[105,117]	–	–
Community operates as legal entity	–	–	[127]

important for CSC that the community operates and is recognised as a legal entity.

> Based on these characteristics, CSC is defined as a community-oriented framework which operates as a legal entity and focuses on creating shared benefits for local communities. The system is typically bound by the local LV network or a small geographical region. Participants are typically small-scale consumers and prosumers, and ownership of generation assets can be shared within the community.

To facilitate the process of identifying which model a project is most similar to, in Appendix B a tool is provided that allows for the classification of projects into P2P, TE or CSC based on characteristics.

6. Conclusion

This paper aimed to answer the following research question :*what are the key defining characteristics of energy systems labelled as Peer-to-Peer, Community/Collective Self-Consumption or Transactive Energy, as outlined in the literature and by stakeholders?* Findings are based on the results of five expert group interviews, representing a wide range of disciplinary and sectoral perspectives across 13 countries, as well as a systematic and targeted review of 78 academic papers and 55 non-academic papers. While the expert interviews focused on the shared characteristics between these models, the literature review specifically analysed the characteristics that set these models apart from one another. The common themes identified in the expert interview manifest differently in each individual model as shown in the distinct definitions.

The terms ‘peer-to-peer energy trading’ and ‘transactive energy’ are often used interchangeably in the field, since they have many overlapping characteristics. TE tends to be defined more broadly, while P2P provides more detailed characteristics as regards market design and configuration. CSC is defined to a limited extent in the literature. The analysis of the characteristics used to define the three concepts that have resulted in three descriptive definitions of P2P, TE and CSC (see Section 5.2).

Findings from both analyses, the interviews and the literature review, indicating the characteristics that distinguish P2P/TE/CSC from traditional energy markets are as follows: They are sub-markets that operate within or alongside traditional energy markets. They involve a form of energy trading or sharing; rely on some form of automation of transactions; are characterised by their promotion and support of the local generation and consumption of energy; encompass both geographically-bounded trading and non-geographically bounded trading; and involve trading with or without intermediaries, with price negotiation mechanisms that reflect the aims of the market. The key differences between P2P, TE, and CSC stem from the problems they were designed to tackle and their origins. As these models scale and inevitably interact with new market layers and challenges, they may converge in the future, with distinctions between them becoming a function of local contexts and associated social, technical, and economic constraints.

It should be noted that this analysis was subject to several limitations. First, given the vast amount of literature concerning P2P/TE/CSC, it was only possible to analyse a snapshot of the literature. As noted in Section 2.2, the academic literature was largely dominated by papers modelling different market parameters. To counteract this over-representation of a particular discipline, a more dichotomous and qualitative approach was taken, looking at whether or not a characteristic was present for each term, as opposed to looking at how frequently characteristics were mentioned for each term. This means that in practice, equal weight was given to characteristics that were mentioned a large number of times and those that were mentioned by just a few papers. This can be seen as a defensible approach; given the discrepancy in the number of papers represented by different disciplines, discussing the frequencies of characteristics would have meant amplifying this over-representation. Finally, characteristics were coded based on the explicit mention of that characteristic in the text. It may be that some characteristics were assumed but not explicitly mentioned by certain models.

Nonetheless, this analysis has clear implications for future research and for policy. Recommendations for future research are the following:

- Expand the scope of research beyond modelling. Detailed information on verification processes and licensing frameworks is yet to be provided in the literature.
- Research should be conducted on the scaling up of such models, including on the socio-economic aspects of these models, for instance governance of trading within CSC.
- Expand research on the practicalities of trading energy within CSC models. Research conducted as part of this paper showed that the literature on this topic is significantly lacking.

Recommendations for policymakers and industry stakeholders are the following:

- Promote and provide a dialogue, particularly between different sectors, on aligning their understanding of P2P/TE/CSC models.
- Ensure that the definitions included in legislation and policies reflect the multi-faceted nature of how these models are defined in practice.
- Realise that these models (and thereby their definitions) are evolving quickly and that the research is expanding. Dialogue between industry, academics and policymakers working in the field is therefore crucial.
- Provide definitions in standards, in order to promote interoperability of systems and ensure the safety of consumers playing an active role in these models.

Since this programme of work began, the European Commission has put forward a proposal to enshrine the right to energy sharing for EU citizens [129]. The Commission has defined energy sharing as "self-consumption by active customers of renewable energy generated or stored offsite either from facilities they own, lease, rent in whole or in part or which has been transferred to them by another active customer". However, it is at the discretion of EU countries to transpose this definition into national regulations, and national regulators may wish to propose more nuanced definitions with regards to specific 'energy sharing' models, such as P2P, TE or CSC. A commonly agreed and more detailed definition of these models and their respective goals could support regulators in developing refined definitions in national regulations.

These findings provide a starting point for developing a shared understanding of this class of models, across multiple disciplinary perspectives and applications. This contributes towards enabling knowledge exchange between sectors and disciplines, supporting international collaboration, and deployment of P2P, TE and CSC at scale.

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.

Data availability

The completed differentiation tool including the instructions as shown in Table B.10 is available in the supplementary material, which can be found at https://osf.io/mn7zk/, an open source cloud-based project management platform hosted at OSF (Watson et al., 2020). The supplementary material also contains the full interview guide, the Excel sheet used to calculate the percentage similarity between terms, a full matrix of terms and characteristics associated with one another, and the review search protocol.

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Appendix A. Overview of characteristics and references

See Table A.9.

Appendix B. Differentiation tool for P2P/TE/CSC models

The analysis in Section 4 has shown that while P2P/TE/CSC models all have some features in common, they also have distinct features. This is important because a coherent understanding of these types of models can avoid misunderstandings in communication between regulators and researchers and thus speed up the adoption of LEMs. More specifically, the identification of different concepts can serve policymakers and regulators as a guide to reflect those differences in regulation and therefore provide more certainty and guidance for pilot project stakeholders. In the following, a screening tool to classify a pilot project as either a P2P, TE or CSC model is presented by calculating a similarity index that indicates whether a project is most similar to one concept over the other. In accordance with the approach taken in this research, the similarity index is calculated by using the characteristics associated with P2P, TE, and CSC. The tool is available in the supplementary material of this paper. The differentiation tool was developed by creating a list of all 87 characteristics identified in Section 4.2 that were presented in the categories of 'market or system aims and incentives', 'participant types and scale', 'participant interactions', 'market or system design', 'market or system scale', 'market transactions and settlement' and 'governance and policy'. In order to reduce the size and improve the comprehension of the list of characteristics, the list was screened a second time and the characteristics were assessed for their meaningfulness and uniqueness.

Table B.10
Overview of differentiation tool with example data to calculate similarity index.

Characteristic	Present in pilot	P2P	TE	CSC
Priority on system optimisation		x	x	
Priority on individual benefits	x	x		
Priority on community benefits	x			x
Involves participants of different scales		x		
Focus on small-scale non-commercial individual users	x	x	x	x
Focus on communities (optimisation and metering on community level)				x
Participants are independent and self-interested decision makers	x	x	x	
Active end-user participation	x	x		
Participants have shared energy trading goals				x
Distributed market coordination and management		x	x	
Centralised market coordination and management	x	x	x	
Autonomous grid control			x	
Optimisation at device level			x	
Concept based on sharing economy		x		x
Market-based approach		x	x	
Incentivise user behaviours through price signals		x	x	
Local energy trading or market geographic region	x	x	x	
Virtual energy trading no geographical restrictions		x	x	
Operates on various levels of the grid			x	
Bound by building or block				x
Multi-directional exchange of energy and value	x	x	x	
Energy transactions without intermediary		x	x	
Energy transactions through intermediary		x	x	x
Trading of different classes/attributions of energy	x	x		
Trading of different types of energy (reactive, active)			x	
Participants not selling energy professionally	x	x		
Equal responsibility and rights for all participants		x		
Community operates as legal entity				x
Disruptive business model		x		x
No of characteristics	**10**	**21**	**17**	**10**
No of shared characteristics		**9**	**4**	**3**
Similarity index		**0.43**	**0.24**	**0.3**

Both coders reviewed the list independently, and if a rewording or further description of a characteristic was deemed necessary, the coders discussed any differences and agreed on an updated version of the list. This resulted in the list being reduced to a total of 30 characteristics. 57 characteristics were either removed or merged with others for clarity. The differentiation tool is presented in a table-based format, as shown in Table B.10. In the first column, the key characteristics are presented. In the second column the user can indicate the characteristics that they think are represented in the particular pilot project. The tool is highly dependent on the expertise of the user, and therefore only serves as an indication for the classification of a pilot project. The characteristics entered can then be compared with P2P, TE, and CSC models using columns three to five. The similarity index is calculated by comparing how many of the characteristics found in a pilot project overlap with the characteristics associated with one of the concepts. In the case of the example data used in Table B.10, the pilot project would be most similar to the concept of P2P and least similar to TE, with CSC in between both concepts. It is at the discretion of the user to interpret the results considering all additional contextual and environmental information available on the pilot project. It is recommended to consider both the characteristics presented and the index value calculated to develop an understanding of the type of concept represented in a pilot project. Similarly to the above-presented analyses, this tool is also impacted by the underrepresentation of CSC in the field. In comparison to the concepts P2P and TE, CSC has fewer characteristics associated with it, therefore weakening the informative value of the tool for this concept in particular. The same limitations as the literature review analysis also apply to this tool (see Section 6). As more institutional bodies or standards organisations continue their work on defining and differentiating P2P/TE/CSC models, better and more accurate characteristics can be derived. These refined characteristics can be used to replace the current list of characteristics and thus contribute to an improved version of the differentiation tool, which will lead to more accurate and more widely applicable results.

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