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Original research article

Conceptualizations of smart grids –anomalous and contradictory expert paradigms in transitions of the electricity system

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ABSTRACT

Smart Grids (SGs) are crucial for the transition of electricity grids towards achieving carbon neutrality. Initially, SGs were conceptualized as transformative technologies that would turn grids into complex resilient systems with high adaptive capacity, integrating renewables and leveraging flexibility in supply, storage, and demand, by integrating electricity supply with ICT. This exploratory Q-study aims to define and classify existing SG concepts as perceived by experts worldwide. The study reveals the presence of distinct paradigmatic views on SGs as social-technical systems. While certain paradigms coexist, others display contradictions and are mutually exclusive. Distinct SG-paradigms revolve around various elements such as:

- the allocation of control over distributed energy systems;
- the role of autonomous Microgrid communities;
- demand response in distributed energy management systems as opposed to hierarchical centralized demand side management;
- the empowerment of active end-users.

The most fundamental contradictions arise in determining who holds control within future hybrid polycentric networks composed of interconnected microgrids, where electricity generation, consumption, and exchange occur at the grid's periphery rather than in a hierarchical and centralized manner. The paradigmatic contradictions pose a genuine risk of hindering the realization of SGs as self-healing complex adaptive systems, which was the original intention behind the SG-concept. This limitation jeopardizes the added value of SGs in mitigating climate change and might slow down the transition towards carbon neutral electricity grids.

1. Introduction

The adoption of renewable electricity on a global scale is widely recognized as essential for achieving carbon neutrality in energy supply [1,2]. In order to accomplish this, the electricity grid needs to undergo a transformation. Amin [3] proposed combining information and communication technology (ICT) with electricity grids, which would enable them to become "intelligent." He referred to this concept, along with the transformation of the design, control, and protection of electric power infrastructure into "*a complex adaptive system,*" as the "*Smart Grid*" (SG) [4]. This idea including "grid computing" is increasingly viewed as necessary [5,6,7] to create opportunities for efficient and reliable delivery, as well as to enhance security [8]. The flexibility of SGs is crucial for effectively integrating fluctuating energy sources and accommodating variable consumption in power supply systems [7]. Amin emphasized that SGs would be "capable of self-healing, adaptive, resilient, and sustainable, with the ability to predict under different uncertainties" [1,9,p.2591]. This concept was embraced with high

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Abbreviations: AC, Alternate Current; AMD, Advanced Metering Device; AI, Artificial Intelligence; DC, Direct Current; DES, Distributed Energy Systems; DG, Distributed Generation; DR, Demand Response; DSM, Demand Side Management; DSO, Distribution System Operators; EMS, Energy Management System; ESS, Energy Storage System; EV, Electric vehicles; HV, High Voltage; ICT, Information and Communication Technology; IoT, Internet of Things; LAN, Local Area Network; LEM, Local Energy Market; LV, Low Voltage; MG, MicroGrid; P2P, Peer-to-Peer; PCA, Principal Component Analysis; PV, Photo-Voltaics; RE, Renewable Energy; REC, Renewable Energy Community; RED, (EU's) Renewable Energy Directive; RES, Renewable Energy System; RTP, Real-Time Pricing (−tariffs); SA, Social Acceptance process; SCADA, Supervisory Control and Data Acquisition; SG, Smart Grid; STS, Social-Technical System; TE, Transactive Energy; V2G, Vehicle-to-Grid.

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expectations, but soon contradictory views emerged. Possibly due to differing interpretations in the literature, in policy circles SG has become a fashionable buzzword.

Conceptualizations remain implicit and vague with regards to technological as well as organizational transformations of the power supply system. Technically, an energy system is defined as a system that converts one or more energy flows into energy flows of a different kind [10]. The introduction of SGs primarily as a major change of replacing old technologies with new ones, known as 'architectural innovation' [11], is still dominant in energy research and policy [12,13]. In this approach, human needs and societal functions are assumed to be fixed, when in reality, they are constantly evolving dynamics. Acceptance of innovation [14,15] and transition processes studies [16] highlight the socio-technical system (STS) nature of systems. It is evident that energy systems can be characterized as STS [17,18], and the same applies to different types of SGs [19,20]. Additionally, alongside the term "Smart Grid," there are other loosely defined terms associated with it, such as the "Energy Internet" [21], which incorporates the "Internet of Things" (IoT) [22,23,24]. Beyond being a vague buzzword, the essence of the SG concept lies in its socially constructed nature within the STS approach. The interpretation and attribution of meaning to the concept are not without significance, as they can be influenced by the interests of powerful stakeholders and prevailing knowledge paradigms [25,26,27]. The purpose of this investigation is to systematically examine existing paradigms and discern the subjective distinctions in the interpretation of the SG concept.

2. Primary commitment: adaptive grids

2.1. Research question

Clearly, as societies experience rapid shifts in their electricity demands and technological advancements, the concept of SG is continuously evolving. It is important to recognize that SG goes beyond being a mere trendy buzzword. The SG concept is being promoted, developed, and potentially implemented with diverse objectives and vested interests. Therefore, it is crucial to understand how this evolving concept is currently perceived by experts, who are expected to have a broader perspective beyond the notion that the grid becomes "smart" solely through the application of ICT.

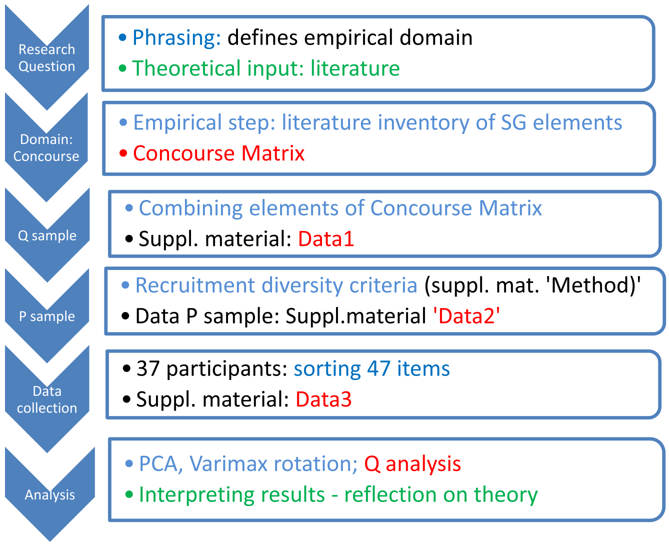

Fig. 1. Sequence of steps in research design.
Blue: process; Green: theory input; Red: empirical results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Existing power grids are complex systems that incorporate machinery, infrastructure, cultural artifacts, business practices, and ecosystems. While they have a physical presence, most aspects of the grid are deeply influenced by socio-political, economic, historical, and sociocultural factors that have become institutionalized [28,29]. The research question aims to investigate the presence of energy paradigms in which SGs play a central role [25,30,31].

What are the key disparities in objectives, design, and perspectives concerning the concept of 'SmartGrid' among experts? How do the social and technical attributes of electricity networks manifest in these contrasting notions? To what degree do these differences encompass paradigms that present challenges for reconciliation?

2.2. Four basic principles

This explorative research question necessitates an examination of the key factors that fundamentally deviate in the attributed characteristics and meanings of all potential elements of SGs as social-technical systems, even including those elements that are primarily considered relevant by other experts. The significance of exploring these incommensurable conceptualizations lies in the recognition that vague concepts operationalized in various ways can lead to "careless and unproductive thinking," hindering both empirical progress and practical application [32].

There are four fundamental principles at play. Firstly, the consensus on the integration of electricity supply with an increasing reliance on information and communication technology (ICT) in SGs. The dynamic control of grids through a combination of digital systems is expected to enhance the ability of both customers and utilities to monitor, control, and predict energy usage [33], thereby facilitating the reliable integration of various generation sources and demand. However, Amin's original concept emphasized the importance of transforming the grid into an *adaptive complex* system [3,34], aligning with the socio-technical system (STS) interpretation of an "*adaptive resource system*" [35]. In this interpretation, the resource is constituted by the natural supply of carbon-free renewable energy sources. This perspective also aligns with the growing recognition of power grids as ecosystems [28], highlighting the need to consider "ecosystem and contextual conditions" with utmost attention [36,37,38].

So the 2nd principle is the expectation that ICT will enhance the *integration of renewable energy (RE) sources* [5]. RE is only available in geographically highly dispersed distributed resources, and therefore generated in numerous distributed energy systems (DES). DES provides supply patterns based on dynamic energy flows, but may also include infrastructures for storage, demand response (DR), and integration with other energy provision (e.g. heat). DES represent a move away from the traditionally rigid centralized grid, that is lacking compatibility and mainly dynamic flexibility. A notable divergence emerged when policy documents began referring to this as "additional to base-load generation capacity" [39], implying the assumptions that renewable energy (RE) is framed as "intermittent" and that "baseload power must be supplied by constant and reliable sources of electricity" [40,27].

Hence, the 3rd principle revolves around *system flexibility*. Essential for self-healing and adaptivity, recovery capabilities have been deemed fundamental for SGs [3,41] overcoming vulnerabilities due to the rigid monoculture of the standardized public electricity grid. The flexibility of all components [42] is facilitated by the integration of ICT, including advanced forms of Artificial Intelligence (AI) [43]. This flexibility is crucial for accommodating variations in net-load by controlling the input or output of power across the grid over time [44], preserving the balance in the system concerning disturbances of power quality with regards frequency and voltage control [45]. The major issue is balancing the gap between varying supply and demand concerning unbalances on different time frames: rapid random fluctuations, slow periodical fluctuations, rare abrupt changes [46], and unbalances between connected systems like heat, gas or hydrogen [47,48].

Table 1

SmartGrid concourse components. All proposed elements of SGs grouped under the four SG principles, with their variants found in the literature, and the number of times (N) these elements are included in items of the Q-sample (see Data1, Suppl. material).

Component in the concourse matrix	Possible terms; alternatives; of similar purport; or essential part of it	N
Information technology		
IC Technology	Digital Technology; Digital information processing	8
ICT monitoring	Sensors; Digital metering;	8
ICT control	IT management; Intelligent management; Intelligent energy systems; Digital management; Meter data management	8
System design (tech)	Grid design; Network design	2
IoT	Internet of Things; Smart home products; Home automation;	2
IoT devices	IoT equipment/assets; Smart electronic devices; Commodity sensors	5
Automated management	Digital management/processing; SmartHomes; Distribution automation; Control algorithm; AI control/management; Fuzzy-logic management	3
Communication (producers to customers)	Smart meter; Advanced metering; Enhanced/ redesigned smart meter; Remote readable meter; Consumption feedback; customer feedback	4
Shared ICT	Co-installed ICT; Co-owned ICT; Common ICT/platforms	2
Distributed ledgers	Blockchain; AI-driven blockchain	4
Renewable energy		
Integrating RE	Integrating / combining RE sources; RE production; Multi-vector microgrid; Multi-carrier (micro-) grid	7
Distributed Generation	DG; Distributed resources; Distribute RE sources	5
MicroGrid (MG)	Mini-grid; DC microgrid; AC microgrid; Islanded grid; Local/Distributed network; Neighborhood area grid	6
Base-load (versus RE loads)	Stable inflexible load/ capacity; Additional RE; Supplementary RE; RE capacity credit	2
Intermittent RE	Unreliable sources; Interrupted sources; Interrupted generation	4
Time / Geographical variety RE production	Fluctuating production; Natural flows following production; Geographical dispersion	8
Power quality control	Quality management; Technical grid control	3
Power quality	Reliability; Continuity; Voltage stability; Frequency stability	4
Protection schemes	Frequency /Voltage control; Outage management; Droop control; Model predictive control; Protection relays; Faul management	2
Resilience	Supply reliability; Security of supply; (decreased) Vulnerability	5
Social-technical system		
Organizational system design	STS; Socio-technical system; Business ecology; Industrial ecology	4
DSO management	Distribution System Organization's management; DSO control; Utility control; Network managers	5
Grid management	Grid manager's control; SCADA control; Central grid/pubic network control; Grid system operation	4
Central grid	Existing grid; Public grid; National grid; Central grid structure	5
Institutional system lock-in	Institutional context; Institutional frame	5
Central/national grid control	Central grid management; Centralized paradigm; control hierarchy	5
Existing Grid	Public grid; Current grid; Current network; Back-up network/grid	6
(acceptability) Tariff system	Billing system; Pricing schemes; Rates	3
Acceptance of control	(customer) Acceptance; Confidence; Legitimacy	5
Trust	Consumer trust; Mutual trust	3
Regulatory frames	Legal frameworks; Regulator's regime	2
Energy transition	Zero carbon /Carbon free Tr.; Transforming energy systems	3
DES based microgrid	RE/ DG in LAN based system; Integrated local distributed system	5
Distributed Energy Systems	DES; DER, DERM (Distributed energy resources); SLEs, Smart Local Energy system;	7
Interconnected integrated MGs	Multi-microgrids; Multi-vector microgrids	4
DG	Distributed generation; Distributed production	3
Polycentricity	Multi-layered hybrid; Multi-centred	3
Active (vs passive) consumers	Active end-users; End-user participation	6
Prosumer	Prosumers community; Self-consumption; Consumer's self production	4
MG community	Energy community; RE Community; Positive energy district; Positive vs negative-paradigm; Community control; Energy commons; Shared RE	4
Distributed infrastructures	Distributed facilities/assets; Distributed capacity	5
Local Energy Market	LEM; Energy sub-market; Local trading system; Decentral market; Transactive Energy (TE) trading;	7
Co-production (energy)	Cooperation in production; Production cooperatives; Cooperating prosumers; Collective prosumers; Aggregated prosumers	5
Prosumers' control	Prosumers' agency; Prosumer based EMS;	4
Co-production (of DES infra)	Cooperation in establishing DES infra; (business) Ecosystem; Co-creation; Collaborative DES construction; Sharing DES investments	4
Flexibility & balance		
System flexibility	Flexibility of power supply; Flexible capacities; Responsive capacities	3
Varying demand	Fluctuating demand; Fluctuating loads	4
Flexible demand	Adaptive demand; Adaptive loads; Smart loads	6
Balance RE–demand	Optimization RE-demand; Real-time balancing/ optimization; Transactive (TE) control/balancing	7
RE curtailment	RE load curtailment; RE dispatch; Generation dispatch; Switched-off RES; Cut-off RE	2
Storage	Storage systems; Storage infrastructures; Storage capacity; Energy storage systems; ESS (wide range storage tech's referred)	5
E mobility	V2G, Vehicle-to-grid; Smart recharging; EV uploading; Plug-in hybrid .	4
DSM (by grid manager/utility)	Controlled demand response; Critical peak control; Direct load control; Capacity control/management;	6
System efficiency	Optimized system; Optimized system costs	3
Internal DR	DR within MG; DR to DES; DR to DER	5
DR (to DES, among prosumers)	Integrated Demand Response; automated demand response	6
Internal control (MG)	Energy management system (EMS); MEM (MG Energy Management system); MG control algorithm; Autonomous MG; MG droop control; Energy service interface; Predictive control; MG Central Controller; MG self-control; Distributed control;	4
Flexible Tariffs	Flexible prices; Dynamic tariffs; Variable tariff; Variable/Real-time billing	4
Real-time pricing	RTP; Supply dependent pricing	5
P2P trading	Peer-to-peer trading; P2P pay-off	2

(*continued on next page*)

Table 1 (*continued*)

Component in the concourse matrix	Possible terms; alternatives; of similar purport; or essential part of it	N
P2P delivery	P2P exchange; Prosumer-consumer delivery; Mutual delivery	5
Sharing energy (streams)	Power sharing; Collective power / energy; P2P balancing	4
Sharing resources (capacities)	Sharing infra (DES); Collective systems (DES); (ST)ecosystems; Collective generation capacity; Collective storage	4
User's acceptance of devices	Consumers acceptance; Adoption smart devices	4
AC/ DC microgrid	Low voltage DC grid; Microgrid AC/DC invertors	2

The fourth principle is the *socio-technical systems* (STS) approach, which recognizes that consensus on the application of ICT, deployment of renewable energy (RE), and system flexibility may disintegrate when discussing the objectives, agents in control, and conflicts between RE and conventional baseload power. Each element within the fundamental principles of SGs can be assessed differently. Therefore, it is crucial to inventory these elements as one important step in empirical research (Section 4.1). First, we provide a brief overview of all steps in the overall study design.

3. Method

3.1. *Design: structured qualification*

Sophisticated notions regarding nascent evolving concepts are typically attributed to experts within the field. In the context of SGs, this refers to professionals engaged in academic research and those involved in SG applications. However, the research question is not centered on establishing a representative consensus among experts in the realm of SGs. Instead, it aims to identify the specific elements within SGs that elicit distinct evaluations, and to interpret these into fundamental disparities and paradigmatic perspectives.

Investigating all elements that contribute to significant conceptual variations does not involve gauging personal preferences through interviews or employing participatory methods like focus groups or Delphi studies [49]. Rather, a suitable approach is Q-methodology, which was introduced in the 1930s [50], but remains relatively unfamiliar. Q-methodology compares comprehensive profiles of individuals across a predetermined set of cases selected to encompass all potential subjectivities. It avoids the comparison of measurements between individuals or their stances on pre-determined topics, such as questionnaire items.

Q-methodology is increasingly being utilized to explore distinct subjective yet structural viewpoints in domains like infrastructure, spatial development, and land use [51,52]. More broadly, also other sustainability domains [53,54], or underlying concepts like vulnerability and resilience [55]. These domains encompass contested energy topics and technologies that perpetuate carbon lock-in, e.g. shale gas fracking or carbon capture and sequestration [56,57]. Q method has also been used to study renewables like photovoltaics [58], wind energy [59,60], hydroelectric power [61], as well as grid management aspects like smart metering and demand-side management [62,63].

Typically, this exploratory methodology serves as a robust and foundational step preceding hypothesis testing investigations [48,64]. For a comprehensive description of the Q-method, procedural study details, and data, please refer to the supplementary material.

3.2. *Procedure*

The essential process of Q studies [65,66] consists of six steps (Fig. 1). The prime step, the research question, does not ask for hypothesis testing. Although the design emphasizes exploratory qualification, data collection and analysis adhere to a strict formal quantification model, facilitating straightforward replication.

Table 2
Variety of experts in the P sample.

Geographical variety
Countries, origin of the recruited P-sample (employment and academic education)

Continent	N	Countries included in the P sample; total 27.
North America	4.5	Canada, United States
South America	3	Argentina, Brazil, Chile
Europe	12.5	Denmark, France, Germany, Italy, Netherlands, Poland, Spain, Sweden, Switzerland, United Kingdom
Africa	2	Morocco, South-Africa
Asia	12.5	China, India, Iran, Israel, Japan, Pakistan, South-Korea, Taiwan
Pacific	2.5	Australia, New Zealand

Academic discipline

Natural science or technology	Natural + Social Science	Social Science
17	3	17

Expertise category

Research, Academy or Research Centre	RE, Energy company; DSO, Government
19	18

Gender

Female	Male
18	19

Step two involves the definition of a comprehensive set of optional issues called the 'concourse,' which encompasses the entire domain under study. To mitigate researcher bias, a *concourse matrix* is constructed [67]. Unlike a review that summarizes the current state of understanding, our concourse matrix begins with four SG principles mentioned in Section 2: ICT, RE, STS, and flexibility. These aspects serve as the basis for constructing four subsets (Table 1), all derived from academic literature, covering the full range of possible components within the scope of the study. Unlike in R-studies where researchers select relevant variables [68], in the concourse, all components proposed in academic publications are included. The items are devoid of any predefined relevance or validity, as Q-studies reserve the determination of relevance and validity exclusively for the participants.

The third step involves creating the Q-sample, which comprises a set of statements intended to encompass all possible components within the concourse. To ensure comprehensive coverage, all elements in the concourse matrix (Table 1) have been included multiple times in the Q-set of 47 statements (Suppl. Material: Data1). Several of these statements are commonly found in the literature, such as statement **BG,** which rephrases one of the numerous definitions found in the literature [69]: 'The core of smart grids is *flexibility* created by *ICT monitoring* and *control* serving the *integration* of *renewable energy*-based *co-production* in *Distributed Energy Systems*' (Table 1, elements cursive).

Step four involves defining the population of individuals who hold relevant views. In a Q-study, the participants serve as a means to collect data about the cases. The P-sample does not aim for representativeness of the expert population; instead, it seeks to achieve optimal variation among the participants. All data of the participants' background are provided in the supplementary material: Data2.

To ensure the inclusion of all relevant perspectives, the following criteria have been applied, all exposed in Table 2. The prime criterion was *"expertise."* Numerous academics are involved in the development and implementation of SG-elements within the STS-framework of power supply, including ICT, RE integration, and flexibility options. Additionally, there are academic researchers investigating these elements. An equal number of expert participants from these two categories were recruited. The *multidisciplinary* nature of the domain shows experts with a scientific or technical education – physics, energy, electricity, and computer science –on equal measure as experts with a social-scientific background – economics, political science, geography, and sociology. As research and development of SGs are conducted globally, experts were recruited to ensure maximum *geographical diversity*, selected from six continents and 27 countries. Finally, the table 2 shows that the sample was *gender*-balanced.

In step five, each participant in the P-sample was tasked with sorting the randomly coded 47 statements within a predefined framework of distribution. No systematic differences were found among the data collection methods: face-to-face ($n = 7$), online ($n = 11$), and solitaire/home ($n = 19$).

Step six, data processing and analysis, strictly adhered to formal criteria. Initially, an "inverted factor analysis" technique [50] was employed, utilizing Principle Component Analysis based on individuals' rankings. A criterion of explained variance, with a threshold of more than one participant (EigenValue >2.7), resulted in four components for orthogonal Varimax rotation, with 79 % total explained variance. The resulting distinctive perspectives represented paradigmatic views of SGs. These perspectives were further analyzed using normalized factor scores calculated with high factor loadings (>0.50). The results (suppl. Material: Method, table 5) are reported and interpreted in Section 5, "Distinct concepts".

4. Empirical results: the concourse and the Q sample

The initial results of this study focus on method-step 2, the construction of the concourse matrix. This section should not be considered a review, but an inventory of all key phenomena identified in the literature. Table 1 shows them, with most of the varying terms encountered in the literature. In the table they are ordered following the four outlined basic principles, but in their description below we will see that many elements are linked to more than one of the principles.

4.1. First principle: ICT

With the perspective of introducing ICT to the grid, early expectations pointed at the possibilities of real-time management [8] with the potential to facilitate the integration of RE, to adapt demand, and to address various issues in current electricity grids, such as transmission losses, DES integration, emissions reduction, improved billing, and fraud prevention [70,71]. However, the success of these claims heavily relies on how ICT is applied, by whom, and for what purpose. Thus, the Q-items in this study establish links between different forms of ICT and their applications, goals, and control. In most items, ICT is expected to enhance real-time management, improving flexibility to address three types of uncertainties: supply-side uncertainty caused by variable resources, variable demand, and in-between uncertainty resulting from transmission and external factors [72]. As electricity generation transitions from large, dispatch-type, and rigid base-load capacities [40] to more distributed, diverse, and smaller-scale units with inherent variability, the need for system flexibility rapidly increases [73].

In SG research, an emerging trend is the utilization of various optimization approaches and uncertainty mitigation strategies. These include game theory, fuzzy mathematics, stochastic modeling, agent-based modeling, and Monte-Carlo simulations. These approaches often rely on the concept of DES within *microgrids* (MG) [74,75,76,77]. While individual DG units may present challenges, adopting a system approach allows for the consideration of generation and associated loads as one subsystem [78,79]. This approach of examining the system as a whole recognizes the interdependence of various components within the system and emphasizes the importance of treating them as interconnected entities. Then it becomes possible to address issues arising from individual DG units and optimize the overall performance and functionality at the level of the MG.

4.2. Second principle: integration of RE

A MG is composed of interconnected small-scale power generation, storage, and internal distribution systems that function as a unified and controllable entity [80]. Consequently, the energy management system of the MG [81] has emerged as a potential framework for integrating distributed RE sources, energy storage, and demand loads [82,83] Although some MGs operate in island mode, they are typically not disconnected from the larger grid, but by operating in a distributed manner they reduce their control burden on the central grid [80].

Integrated, self-healing MGs are highly compatible with photovoltaics (PV). However, PV power plants are susceptible to materials theft, e.g., copper, while grid-connected PV inverters are vulnerable to hacking and struggle to control AC voltage and frequency. Since PV typically generates DC power, low voltage may be a preferable option for application in MGs, potentially utilizing DC instead of 230V AC [84,85]. MGs are considered as viable solutions for maintaining security and power quality [86]. Nonetheless, DES can introduce issues such as harmonics, steady voltage fluctuation, and flicker when directly connected to the public grid. [87,88].

4.3. Third principle: flexibility

Real-time Demand Response (DR) systems provide additional *flexibility* [89]. Early community energy projects that employed non-automated DR with dynamic tariffs demonstrated direct responses to the generated wind power by adapting equipment usage [90]. However, with clear limitations imposed by social practices [91], that do not align with the expectations of technological experts. Demand Side

Management (DSM) is an evolving concept, aimed at aligning the demand for electric energy services with available distributed and resources [92,p.1]. Its objectives include improving the utilization of the power system, enhancing reliability, and increasing consumer choice while maximizing the penetration of DES [92,p.6]. DSM encompasses measures, such as differentiated tariffs, providing incentives for peak shaving, but increasingly implementing sophisticated real-time control to align direct consumption with DES.

Typically, DSM assumes the existence of an "agent". Who will be that agent implementing real-time control? The level of trust end-users have in it wills significantly impact the acceptance of load control measures [93]. Therefore, DSM faces challenges in gaining *social acceptance* (SA) [10,94]. The adoption and adaptation of end-users' demand will only occur under demanding circumstances. The original objective of DSM was to optimize the use of utilities' baseload capacity [95], and the primary grid DS-managers strategy employed "valley filling" [70]. This even encouraged the use of high-load equipment like electric boilers for recharging during nighttime with time-of-day tariffs. Smart DR could better stimulate direct consumption during day-time (PV), and the shifting of consumption between different resources, particularly those generated by prosumers [96], thereby increasing consumption from self-generated or stored power. By the involvement in investment, installation, and direct utilization the SG concept *active prosumer and consumer participation* becomes essential [97].

From a technological perspectives DR is often seen as a mere response mechanism, with the SG's contribution limited to providing customers with information to make informed decisions about their electricity usage [9 p.1592]. This approach suffers from to issues related to end-user acceptance. Power providers often have simplistic perceptions of how demand is constructed and influenced, with DR as a tariff or program designed to incentivize changes in electricity consumption [98, p.152]. The success of engaging end-users depends on whether a design logic or a user logic is employed for implementation [99]. This relates to the purpose of the scheme and who implements it. Currently, DR is still being proposed with automated dispatch through signals that control equipment [100,101], but the aim shifts to adaptation to DES, beyond the traditional peak-shaving response prompted by utilities in DSM.

Activation of end-users is also about transforming the passive response of into active participation on installing grid infrastructure. This leads to the optimal operation of MGs and effectively improving their economy and stability [102]. Additionally, this active involvement can help reduce the instabilities caused by variable RE [103]. To enable smart management of RE generation, storage, and demand loads, peer-to-peer (P2P) energy exchange within MGs plays a crucial role [104]. Optimization studies often employ game-theoretic approaches, where participants share capacities and exchange energy flows [105,106]. Effective management systems require cooperation and exchange among participants, P2P, as a key principle in organizing energy community structures [107,108]. P2P sharing implies the co-production, trading, and distribution of goods and services in a commons-based manner [109,110,111]]. The governance of these systems involves self-regulation of P2P conditions, including control over the algorithms used in the Energy Management Systems (EMS), to establish trust, safety, and reliability in community grids [30,86,112]. Because SGs aim to optimally integrate RE, cooperation in land use decisions is also essential for RE co-production, ensuring that RE and DES infrastructures are located close to the demand [113,114,115].

Within MGs entities have their own objectives and organizational principles, which are challenging existing public grids. Traditional methods of monitoring grids and metering are rapidly fading away, and with the emergence of P2P-delivery and trading, the increasing importance of storage capacities, and more active end users, a paradigm shift is underway [116]. The mono-central grid management approach appears to be outdated, with MGs managing critical infrastructure for multiple customers, particularly in districts aiming for efficient renewable energy utilization and reliability. This requires an "energy paradigm transition from negative to positive," encompassing storage, energy sharing between buildings, and advanced energy management and control strategies [31]. These MGs can be implemented by prosumers who collaborate within MG communities or in conjunction with grid-managing utilities [38].

Prosumers are a new type of entity that not only produce, consume, store, and exchange energy with other users, but also contribute to the co-production of the distributed infrastructure within the MG's scope [36,117,118]. According to the European organization of Energy Cooperatives, prosumers become part of "energy communities" with initiatives where people have ownership or meaningful involvement in the operation of RE or energy-related services [119,120]. The coproduction by prosumers extends beyond the sharing and trading of electricity, encompassing the collaborative development of the distributed infrastructure within the MG [113].

4.4. Fourth principle: social-technical system

Grids of interconnected MGs [41,121] imply fundamental changes in the organizational model of electricity grids. The flexibility, diversity, and interconnection of DES give rise to a hybrid system that departs from the traditional hierarchical control and mono-centrality. While "decentralized" systems are distributed in nature, DESs are not necessarily decentralized [122,123]. Instead, integrated MG communities function as self-governing components within a broader hybrid system, more accurately described as *polycentric* [37,118], These are social system structures that encompass multiple decision centers, each with limited and autonomous authority, operating under an overarching framework of institutional conditions [124,125]. Polycentrism is believed to enhance the resilience of institutions and making infrastructures more adaptive, the original aim of SGs [3,4], against external shocks of a social, economic, or ecological nature [126].

The shift from intrusive mono-central grid control to a multi-level polycentric network requires significant *institutional transformations*, including comprehensive revisions to legal frameworks governing central grids. These transformations address existing barriers to co-production and P2P energy exchanges, as well as the legally entrenched dominance of incumbent energy companies and Distribution System Operators (DSOs). While policies often vaguely refer to this shift as consumer-centric markets, a more encompassing term for it could be "trading in Local Energy Markets" (LEMs) [127], MG "Transactive Energy" [128,129,130], or "P2P community markets" [131].

Co-production and trading within LEMs potentially also enhance the security and privacy of consumption and trading data [112]. The security of grid energy trading DES without relying on third parties can be achieved by integrating *distributed ledgers* into these systems [132,133] Within their EMS, peers can incorporate negotiations regarding the value of utilizing community members' capacities for generation, space, storage, energy absorption, and all energy transactions. These exchanges are monitored and recorded in anonymous encrypted messaging streams, eliminating the need for a trusted authority, through the application of blockchain technology [76,127,129,134]. This technology can function as a trust-building mechanism for all users, enabling the implementation of smart contracts among MG peers that are securely stored in blocks with cryptographic hashes, thus establishing a new trade infrastructure [135].

All social and technical elements of SGs mentioned in Table 1, rely on perceived justice, encompassing issues of trust and legitimacy. SA is broadly defined as the mutual influence of multi-level decisions over time, regarding all innovative elements of SGs [15]. Energy companies and DSOs are often facing distrust, particularly concerning their business models related to DES [136]. The current data streams from their remote-readable meters face significant SA challenges regarding anonymity and privacy [137]. While blockchain technology is frequently proposed as a grid management tool for utilities and DSOs [138,139], its application in distributed grid management may offer even greater

Table 3

Factor arrays: ideal sorts of 4 factors; ordered from ‘most distinctive’ to ‘consensus’.

Item CODE	Statements in descending order, from most distinctive to concensus	**A** Central grid control	**B** Transform, away from central	**C** MG + Internal control + Flex pricing	**D** DR in MG + DES
AD	The technical restructuring of the power grid through the introduction of intelligence (ICT) will transform the central grid into a polycentric network of interconnected microgrids	-2	1	4	-5
AY	Smart Grid applies devices linked to the Internet-of-Things to create flexible pricing options as a Demand Response strategy to drive the integration of variable distributed generation	−1	4	-4	3
BA	Substantial contribution of ICT-enabled DR to balance demand with variable RE supply requires high end-user adoption of IoT devices under DSO control	4	-1	−3	3
BC	Effective real-time rates are only sufficiently accepted by end users if the tariffs primarily support prosumer’s own Distributed Generation and storage infrastructures	2	0	-3	5
AK	Data processing and internal trade –mutual supply and payment – in local energy markets of co-production, are crucial for any renewable energy community	-3	3	-2	-3
AO	Current regulatory frameworks rigidly reflect the lock-in of the centralized power supply paradigm, which hinders the development of distributed renewable energy microgrids	3	0	3	-2
AU	The carbon-free transition in power supply is primarily depending upon ICT implementation enabling smart DSOs to monitor spatially dispersed intermittent sources and to manage variable demand	3	-3	-3	−1
AC	Microgrids must have an internal control system, which can independently adjust their operation to internal fluctuating loads and supplies, as well as external price signals	-1	4	1	-2
AR	Adaptive security systems in the public grid are needed to counteract vulnerabilities such as communication failures, cyber-attacks related to the IoT, remote metering and remote control	5	−3	2	0
AV	The energy transition consists of centralized power supply systems being rearranged into fully hybrid polycentric systems, connecting and integrating spatially dispersed prosumer-micro-grids.	-2	-2	3	-1
AS	Real-time pricing for demand-side management using ICT monitoring and control, is crucial to integrate intermittent RE sources into the public grid	3	-2	-2	1
AZ	The central power supply paradigm is locked-in by current legal and regulatory frameworks that obstruct decentralization, and microgrid communities with distributed local RE-based energy markets	-1	-1	4	1
AT	Economic and efficient operation of micro-grids must be achieved by effective DR, which requires the adoption of dynamic tariffs for ICT-managed IoT-device loads	-5	1	-1	−3
AG	The introduction of intelligence (ICT; AI) makes the existing electricity grid ‘smart’, which will promote the integration of RE resources and activate end-users	2	−1	-3	2
BU	Co-production of electricity with co-installed and shared DES infrastructure requires legal transformations to enable P2P-delivery and distributed blockchain-based management	-3	3	1	0
AA	Integration of RE resources and flexible loads (demand, storage, E-mobility) requires major realignments of the organizational structure of power supply and grid management	−1	1	5	-1
AJ	Transforming the existing network into a ‘smart’ and renewable network requires IT-enabled flexibility from Distributed Energy Systems, reducing inflexible base-load generation	0	1	3	−2
AQ	Exploitation of DSM by grid operators through ICT for monitoring and control, will meet with great resistance due to distrust in energy companies and governments	2	−2	3	1
AX	The SG integrates shared generation units, storage capacities, and energy flows in microgrids with shared ICT management, based on internal accounting with distributed ledgers (blockchain)	−2	−2	−2	2
BE	The energy transition largely depends on ICT enabling prosumers and end users to balance their demand with distributed RES, to share energy and reduce their exchange with the central grid	2	−1	0	−3
BI	Prosumer’s control over storage, EVs, IoT-equipment, and automated demand-response is essential for achieving acceptance and activation of consumers in energy communities	−3	2	0	1
AE	Centralized control in public grids declines significantly in favor of local Peer-2-Peer energy markets due to cooperative self-control with distributed ledgers and distributed ICT management systems	1	5	0	0
BF	Local energy markets (LEMs) with reciprocal P2P exchange and real-time pricing will match increasing RE power production more closely to consumption than the centralized market	−1	3	−1	1
AI	In P2P microgrids, local market prices (independent from public grid tariffs), are crucial for Demand Response in order to integrate the variable supply of distributed energy systems	0	2	0	−2
BB	Direct connection of large distributed RE power units causes grid instability; this requires intelligent control and curtailment of RE loads to protect reliable base-load generation in power grids	−4	−5	−2	0
AM	Distributed storage capacity in microgrids is the main tool to balance different variable RE sources with each other and with variable demand	1	−2	0	3
BK	Adoption of smart IoT devices and ICT deployed for demand adaptation to meet fluctuating production, relies heavily on control among prosumers over the installation	−2	2	−1	2
BO	Distributed energy systems require microgrids with adaptive internal protection schemes, combining a variety of storage, digital monitoring, and control systems	2	−1	−1	2
BP	Digital platforms and use of distributed ledgers (blockchain) can be applied to balance distributed RE generation and demand in microgrids; they are crucial for prosumer’s trust in future polycentric grids	3	0	1	−1
BS	Confidence issues around energy companies and governments create problems with imposed public smart grids: e.g., resistance to controlling ICT and real-time tariffs and little demand response	−2	−2	−1	2

(*continued on next page*)

Table 3 (*continued*)

Item CODE	Statements in descending order, from most distinctive to concensus	**A** Central grid control	**B** Transform, away from central	**C** MG + Internal control + Flex pricing	**D** DR in MG + DES
BJ	Distributed energy resources are most efficiently shared and coordinated within decentralized microgrids	2	0	2	4
AW	The introduction of ICT for (inter-)national central grid planning will serve base-load generation capacity, reducing RES to merely planned on top of that	−1	−4	−4	−4
AN	Automated management (DSM) of Internet-of-Things -connected devices by power or grid-managing DSOs, is the key tool to balance RE resources with demand	0	−3	0	0
AL	Levels of prosumer's control over smart-devices – batteries, EVs, demand response, IoT-devices – is the prime determinant of acceptance and participation in local energy markets	4	3	1	1
BQ	Willingness to accept DSM, direct load regulation by utilities, remains low compared to DR, demand response on prosumer's own power generation in prosumer-controlled DES microgrids	1	2	2	−1
BR	Exploitation of geographically dispersed resources implies distributed energy systems (DES) which will increase the efficiency of the overall energy system	0	1	−2	−1
BD	'Smart' in the grid means activating end users through ICT and the roll-out of smart meters, as these provide information for utilities and new flexible price signals towards consumers	0	0	0	3
AB	The socio-technical nature of the smart grid is emphasized by the combination of business ecosystems and the industrial ecosystem of the smart grid	−2	0	−1	1
AF	Distributed Energy Systems in microgrids require strong public grid intelligence (ICT) to deal with failures in the distributed power generation and storage systems	1	−1	1	−2
BM	Influencing flexible loads (demand and storage) to integrate RE resources requires a completely restructured institutional design (control, ownership, organization, management) of grids and power supply	0	2	2	0
BN	Storage capacity, in combination with internal demand response systems, becomes an integral part of reliable and efficient distributed generation from variable RE sources	1	0	2	4
BH	Increasing variety among Distributed Energy Systems will result in more resilient power supply, partly as a result from the emergence of a variety in AC/DC and low voltage microgrids	0	1	2	0
BG	The core of Smart Grids is flexibility created by ICT monitoring and control, that is serving the integration of renewable energy-based co-production in Distributed Energy Systems	1	1	1	−1
BT	To enable smart management of Distributed Generation, storage and demand loads, energy sharing with co-production based on P2P exchange between prosumers is crucial	1	2	1	2
AH	The essence of the smart grid is to prevent network unreliability by real-time monitoring of sudden variations, and accordingly cutting-off loads from RE units	−3	−3	−1	−3
BL	A cornerstone of the SG is the grid operator's (or DSOs) centralized control of the of batteries in EVs, to balance the AC frequency, to provide emergency power and to 'shave' peak demand	−1	−1	−2	−2
AP	The smart grid implies communication from producers – with variable sources – directed to end-users, in order to apply ICT for adapting user's demand	−4	−4	−5	−4

advantages [120]. Blockchain creates a level of independence from third parties, fostering mutual trust among prosumers [140]. Similar to automated DSM the remote-readable meters used by DSOs already face SA challenges [94,141]. Evidence from smart grid initiatives suggests that without procedural justice and end-user control in advanced metering and automated DSM, these initiatives are unlikely to succeed [142,143].

The importance of trust and acceptance highlights concepts such as energy democracy [144,145], with a potential convergence between community energy and MGs [119,146]. Consequently, SGs require not only changes in the physical infrastructure but also in the organization and governance of power supply. The knowledge, skills, legal frameworks and policy, all deeply ingrained in the centralized management paradigm, are not inevitable [147]. They are not laws of nature, as electricity grids are shaped by institutional arrangements based on norms and rules. These standards have become deeply entrenched in the existing infrastructure, and due to institutional lock-in factors, there is a strong resistance to change and a high degree of institutional isomorphism. Professionalism in the sector is closely associated with these normative components [148], meaning that experts working in the field may adhere to these paradigmatic standards.

The innovation process of reshaping monocentral power supply systems into SGs involves new technologies, 'hardware'. However, it necessitates even more elements of *social innovations* [14,149], such as new organizational structures, actors, control mechanisms, property divisions, and management models. The hard infrastructures components of electricity grids are relatively inflexible due to their large size, difficulty in replacement, and lifespans spanning several decades. Economically, their existence involves substantial sunk costs. The institutional determinants of this inertia in practices and thinking patterns, rooted in historical developments, have been widely recognized as inhibitory factors in the adoption of innovation processes [29,150], also impeding innovative thinking about SGs [15,19,30]. In fact, they can give rise to fundamental contradictions, as the evidence presented in the next section will demonstrate.

5. Results: distinct concepts

Ultimately, all elements (Table 1) were combined and used multiple times to formulate the items in the Q sample (Suppl, material: Data1). The ranking of these items by 37 experts was analyzed according to the methodology outlined in Section 3 (and more details in additional material: Method). This analysis revealed distinct conceptualizations, which were represented by four different types of 'imaginary experts' ('factors' in the data). For substantive reasons these factors are discussed in the order of A, D, B, C, with references for providing more context.

The paradigms have limited similarities, with only two statements not significantly differentiating for any of the four types. Interestingly, these statements pertain to obvious elements of SGs that were ranked as relatively irrelevant. Specifically, the notion that SGs involve communication from producers using ICT as a tool to adapt to end-use was considered 'irrelevant,' possibly trivial, or denied (item **AP**). Similarly, the centralized control of local assets such as storage and EVs by grid operators was moderately downplayed by all (**BL**).

5.1. Paradigm I: ICT for hierarchical central control

The first distinct conceptualization (**A**, Table 3; Fig. 2) places significant emphasis on technology and the utilization of ICT for hierarchical control in the central public grid. The underlying premise of this *mono-central/tech paradigm* is that innovative and adaptive technologies aim to mitigate potential vulnerabilities related to communication failures, cyber-attacks, and the intermittent nature of RE. In this conceptualization, security systems in the public grid address communication failures and cyber-attacks, particularly in relation to IoT-devices and remote metering at the end-user level (**AR**).

This conceptualization embraces the use of innovative technologies such as digital platforms utilizing blockchain [151] to facilitate the balancing of DG within a polycentric grid (**BP**). Real-time pricing and ICT monitoring of dispersed intermittent sources (**AS**) are combined to achieve DSM of variable demands (**AU**). DSOs are expected to control DSM independently of automated consumer-controlled DR and storage devices within microgrids (**AT, BI**). Aligned with this tech-inspired central control paradigm, new private commercial *congestion service companies* are rapidly emerging. These companies primarily apply DSM through dispatch in exchange for discounts and centralized storage management [152,153].

There are three other perspectives, each exhibiting significant deviations from paradigm I. However, the most significant contradiction lies within this "technology first" factor A itself. Completely inverted views from three out of ten experts highlight the contradictory nature of essential SG components (**—A,** Fig. 2). These experts acknowledge the importance of technology, but they do not support central control. Instead, they advocate for efficient *distributed control* (**AT**) and real-time monitoring of sudden variations to ensure grid reliability and address instabilities RE power units (**AH;BB**). This contrasting perspective also supports the ICT-controlled adjustment of demand loads by RE-producers (**AP**) and potentially restricts the utilization of RE to safeguard base-load capacity (**BB**). Even though it contradicts the objective of reducing CO_2 emissions and integrating flexibility [42], RE curtailment is presently a practiced approach [154] that is only endorsed in paradigm I. All other conceptualizations reject the grid operator's or DSOs' centralized control, as well as the SG as a means of protecting base-load generation (**AW**).

5.2. Paradigm II: real-time rates for distributed generation and storage

Conceptualization **D** (Table 3, Fig. 2) also maintains a connection with current grid managers. It advocates for the implementation of effective real-time rates to facilitate the development of *DG and storage infrastructure within MGs* (**BC;BN**). These MGs are owned and operated by prosumers [155]. By combining storage capacity [156] with internal DR it enables the reliable and efficient integration of *variable* RE sources with variable demand loads (**AM;AY**). Additionally, this conceptualization places emphasis on the significance of ICT and the deployment of remote automated digital meters, commonly referred to as "smart meters" (**BD**).

Similar to paradigm I, a minority of experts (3) expressed a contradictory conceptualization (**—D**, Fig. 2) compared to the views of the other eight experts. This minority lacks confidence in the idea that the introduction of ICT will actively engage end-users (**BD**) and transform the centralized grid into a network of interconnected microgrids (**AD**). Instead, they advocate for legal transformations that promote co-production, DES, MGs, DR, and consumer control over storage and EV-loads (**AT;AB**). Despite their strong belief in technology, they perceive it as a catalyst for P2P energy delivery (**AI**) rather than centralization.

5.3. Paradigm III: autonomous MicroGrids

The other two concepts show a clear trend towards moving away from central control and towards DES and MGs as the core components of SGs. "Ideal" experts **B** and **C** both agree, in contrast to **A** and **D**, that DSM conducted by central grid operators is undesirable and irrealistic. They expect that end users will have low willingness to allow utilities to control DSM (**BQ**). Instead, concepts **B** and **C** both emphasize the importance of influencing flexible loads – by DR and storage – to integrate RE within systems of co-production (**BM;BT**).

However, paradigms III (**B**) and IV (**C**) diverge in their views on MGs with DES: III sees MGs primarily as *local markets*, while IV considers them as *collaborative units of co-production* (**AY;BF**). The *autonomous MGs* paradigm (III, **B** Table 2, Fig. 2) represents a significant departure from the centralized grid model (**AE**). It strongly advocates for the widespread implementation of DES within MGs, where information, communication, and trading occur in decentralized P2P-markets independent from central intermediaries (**BU;BF**). This conceptualization is supported by advanced distributed ledger technologies, such as blockchain, which facilitate internal accounting and transactions [157]. The key idea is to enable the seamless integration of distributed and variable generation from RE sources, along with shared storage capacities and energy flows, all facilitated by ICT. This integration necessitates the establishment of P2P energy markets within MGs, allowing for adaptive and efficient energy management (**AI**). The interconnected loads and DES devices within MGs act as single controllable entities with respect to the public grid [158].

MGs are supposed to operate independently of the central grid, having their own internal control systems that can adjust to fluctuating loads and supplies, as well as to external price signals. The internal EMS allows for more flexible and localized management of RE matched more closely to consumption [159]. The SG may then accordingly be defined as "mutually connected and integrated MGs that can monitor and heal themselves" [3 p.572,19,41]. Interconnection between neighboring MGs enlarges the number of flexibility sources available to all subsystems [160]. Enhancing resilience and limiting vulnerability to disruptions, such as communication failures or cyber-attacks, is emphatically not attributed to public grid management (**AR**), but to MGs internal self-sustained EMS's that may even operate in an islanded mode during public grid failures [161].

Similarly, IoT-connected devices can be used for DR, and the efficient utilization of local storage capacity can involve flexible, real-time pricing (**BF**). To ensure the success of P2P microgrids, it is essential to establish the necessary infrastructure and legal frameworks that facilitate the exchange of energy and payments among participants. This includes prosumers' co-production of electricity within communities where multiple parties share the costs and benefits of RE and other DES (**AK**). The significance of DR through energy management systems in autonomous microgrids is underscored by the recognition of trust issues associated with DSM in centralized public grids. Due to limited confidence in energy companies and governments (**AQ**), this leads to a loss of control and anticipated resistance to real-time tariffs [162]. Moreover, the transition towards distributed systems of RE co-production in RE communities and the adoption of MGs EMS necessitate substantial legal and regulatory changes (**BU**).

5.4. Paradigm IV: DES in new institutional settings

The last conceptualization (**C**, Table 3, Fig. 2) recognizes the need to realign power supply systems that are currently institutionalized under historical governance rules that favor centralized electricity infrastructures and utilities [163]. Such transformations are driven by the extensive introduction of ICT and are required for the integration of RE and flexible loads. This necessitates the development of MG communities with distributed local RE-based energy sharing and co-production (**AA;AD**). These transformations are hindered by the lock-in of the

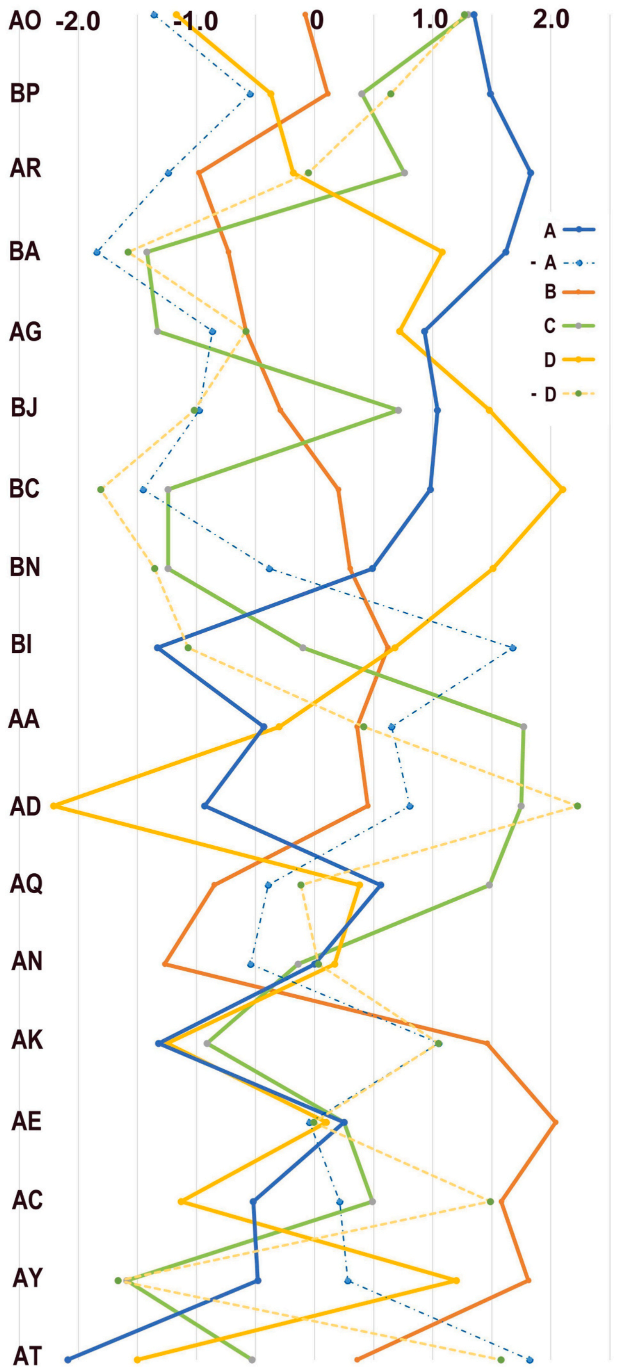

Fig. 2. Most distinguishing statements: the 2 most distinguishing statements for each factor have been included.
Standardized scores (z), that translate into ideal rankings as shown in Table 3.

central power supply paradigm embedded in legal and regulatory frameworks (**AZ**). These rules currently tend to frame digital platforms within sharing contexts primarily as centralized and commercially profit-driven [164]. There is an outspoken rejection of the possibility that the implementation of ICT alone will make the grid 'smart' (**AG**).

The move away from centralization is not one-dimensionally "decentralization" [124] but rather a shift towards a hybrid *polycentric* grid [125,163] of interconnected distributed systems in MGs (**AV**). Expectations are low regarding balancing demand by DSO-control (**BA**). The central public grid's DSM is considered irrelevant, partly due to consumers' distrust of energy companies and governments (**BC;AQ**). Instead of using flexibilities to support base-load generation, the flexibility from DESs establishes an ICT-enabled 'smart' and renewable network (**AJ**). These visions are in line with the original idea of a complex adaptive resilient electricity grid, and hence, the SG adding to the reliability of power supply is rated higher than in the other conceptualizations (**BH**).

6. Conclusions and implications

6.1. *Counterproductive conceptualizations*

The most significant contrast among the four paradigms lies between centralized power generation with hierarchic control versus hybrid polycentric models with primary distributed control and a coexisting public grid managing larger central capacities. It is evident that there are distinct subjective expert views on the nature, structure, and value of SGs. However, less expected but alarming is that within two paradigms, the predominance of technology and central control reveals completely contradictory views. These views do not only coexist but are also mutually exclusive, which is related to the fundamental contradiction between polycentricity and the preconceived hierarchy inherent in centralist systems.

Currently, in technical terms, most electricity systems have decentralized primary control, followed by secondary and tertiary central control. This refers to the order of inspection, but not to the objectives. When the priority in control over power deployment shifts towards DES first, followed by the deployment of more centrally controlled capabilities on top of that, the nature of the grid changes to polycentric. It then becomes a complex adaptive system, avoiding the vulnerable monoculture of the rigid, but increasingly fragile central grid [28], which was the original intention of the smart grid [2,3]. Polycentric systems explicitly acknowledge the importance of local control, experimentation, learning, and adaptation. They are based on a different behavioral theory of human action that also recognizes the influence of context on trust levels and reciprocity [124]. Hence, the strongest contradictions arise from the challenges of transitioning from dominant centralized grid topologies to models where power is generated, consumed, and exchanged at the grid's edge, making it hybrid and primarily distributed [165]. The mono-central/tech vision is most similar to industry-driven initiatives like the *SuperGrid*, a model designed to facilitate large-scale power generation in remote areas for transmission to consumption centers, with the main goal of enhancing the electricity market [166, pp.383]. However, evidence suggests that the central/decentral framework falls short in envisioning future power supply. The centralized Supergrid model creates significant conflicts for business models, energy finance, and grid operation [167], so this model seems mutually exclusive with hybrid SG approaches.

6.2. *Microgrids*

The "inventor" of the SG places MGs at the center of the concept: "A smart grid consists of a series of independent small power systems, or 'microgrids,' linked by a stronger, smarter high-voltage power grid backbone" [34]. Despite this, some paradigms do not recognize this crucial role, as MGs are only prominent in two distinct paradigms. One with a focus on financial elements such as trading, local markets, and dynamic, flexible pricing for DR, and one that emphasizes cooperation, community, co-production, sharing infrastructures, and distributed energy management. MGs are presumed to serve all four SG principles:

(1) *Integrating more RE*; MGs imply the input of distributed RE sources with high geographic dispersion, which has been known for a long time to enable replacement of inflexible baseload capacity, as dispersion improves the capacity credit of variable renewables [168]. Additionally, MG energy management systems (EMSs) integrate different sources and demands from multiple locations

[169], thereby enhancing the feasibility of investments in DES infrastructure closer to the demand.
(2) *Enhancing flexibility* by addressing DR more effectively than DSM by central grid managers, as DR in MGs can improve the installed distributed energy source capacity.
(3) Requiring the development and installation of different kinds of *ICT* compared to central grid management.
(4) Playing on the power grid's *STS character* by shaping better conditions for the contribution of *activated end-users* [97,170], as automated solutions combined with dynamic pricing require active end-user acceptance, where it helps that in MGs the users are in charge. The development and deployment of the SG depend on whether end-users are treated merely as customers using the currently deployed digital meters by DSOs, or as active consumers of a full range of new energy services and applications [12].

The fundamental deviating paradigmatic view on MGs also imply that utilities are facing the challenge of active end-user governed MGs. To survive, they should seriously engage in customer-side business models. However, in practice, they tend to resist these changes and defend current utility business models [171], and overall end-user engagement in smart energy technology projects has been largely tokenistic [172]. It is likely that utilities will continue to keep their EMS algorithms secret and non-transparent, which will result in low trust and problematic acceptance [93]. So opposed paradigms are likely to create SG implementation conflicts, as MGs and self-contained EMSs linked to community energy challenge the SG concepts that aim to enhance the hierarchy of central grids with ICT. The latter tries to allow DSOs and utilities to gain greater control over DG, storage, and end-user loads.

The socio-political battle over who controls end-users and prosumers [173,37] touches on values, such as the meaning of 'smart' [174], and significant concepts like 'Energy Democracy' and Renewable Energy Communities [106,175]. New policies reluctantly support Renewable Energy Communities and community energy, such as the EU's RED II proposal for energy communities as a social model [176,177], which implies co-production in MGs.

6.3. P2P and co-production

Active users must cooperate in various forms of coproduction to facilitate the deployment of DES. Simply relying on policy or market conditions to render users "active" is inadequate. Participation in distributed systems requires acts of cooperation and coproduction [178]. With this cooperation new socio-technical configurations of micro-generation and other DES infrastructures can be installed, space secured, management and maintenance can be organized, and a MG's internal energy management system can be set up [179,113]. The resulting system's diversity and flexibility reflect the original SG idea as an adaptive, complex multi-level resource system [3,4,35,124]. The hybrid grid, consisting of substantial DES in MGs backed up by larger-scale national grids, becomes an adaptive system governed and managed in a polycentric manner, a key to enhanced robustness [126]. It combines technical and social innovation representing an essential institutional transformation [18] in the STS of electricity grids [180].

Fully irrelevant in the central/tech paradigm, but pivotal element in two paradigms, is P2P exchange. Some studies on P2P trading also address 'virtual power plants' [181] with RE-generated power traded among prosumers and exchanged using public grid connections. This model differs from P2P delivery, which implies physical energy flows among prosumers and their storage systems in MGs [182]. P2P becomes a key element in the internal EMS, making the MG an ideal digitally controllable and coordinated load [86]. It requires advanced meters that can communicate with each other, far beyond the currently installed remotely readable meters [137,141,142]. From a polycentric grid management perspective, any DES-microgrid may be regarded as one unit, performing an independent role of internal active and reactive power regulation, frequency, and voltage control [183,184] Solid institutionalization of P2P by creating legal foundations and redefining property and control of distributed capacities [185] becomes a top priority transition policy. Similarly, new policies are required for establishing new regimes for transforming the grid to integrate co-produced collective storage in MGs [156,186].

7. Discussing implications for research and policy

An added value of the applied Q methodology is that it showed only very limited disciplinary bias among experts. There was a moderate difference on paradigm IV, 'DES in new institutional settings'. Technical and natural sciences disciplines mildly dismissive on the one hand, and social and multidisciplinary sciences clearly supportive on the other hand (Supplementary material', 'Method': table 7). The former reveals ignorance, denial, or underestimation of social components of socio-technical systems as SGs are [183,187]. It may also reflect the underexposure of the role of end-users in the techno-economic SG literature, or bias in understanding what end-users actually are [188]. Paradigmatic biases also exist among social scientists, as some either take the centralized system for granted and tend to call anything else "decentralized," or advocate for a fully distributed smart grid [189]. The emphasis on community energy and energy democracy is often expressed without substantive concerns about how energy systems should be physically shaped.

The broad range of components of SGs in the Q sample has forced experts to express themselves also about social dimensions of SGs that are underexposed in the social-scientific literature. While social studies focusing on the term SmartGrid applied theories targeting the social-technical side, such as *sociotechnical imaginaries*, the *human-technology relationship*, and *social practice theory* [189], they hardly cover the *system side* of STSs. Consequently, some of the most appropriate social theories are lacking. The Institutional Analysis and Development framework [190,191,192] covers institutions, multi-level governance, and policy regimes. Combined with the Social-Ecological Systems framework [35,36,37] these generate necessary theoretical synthesis, that is helpful to understand how coproduction, diversity, polycentric governance, and self-governance add to resilience, and adaptive complexity of systems. These were exactly the major reasons to introduce the SG concept [3,4] and polycentric governance [113,124,175].

With regards active end-users, theories on coproduction requiring material participation beyond social participation become relevant [193,194]. Active users must cooperate in various forms of coproduction to facilitate the deployment of DES. Simply relying on policy or market conditions to render users "active" is inadequate. Recently, for example this was evidenced in a MG acceptance study: "restraining forces are more important than driving forces and therefore governments need to tackle the problem of social acceptance of smart grids before focusing on mainly technological aspects in their long-term energy and environmental policies" [195].

Existing rules and powerful actors hinder cooperation in MG communities. To accept prosumers' required commitment to most SG elements it is crucial to provide them with recognition, procedural and distributional justice with regards all operations and activities. This poses a challenge to the legitimacy of current rules, laws, and the dominant positions held by actors within electricity systems. This institutional framework plays a vital role in establishing legitimacy by creating favorable conditions for local participation and end-user involvement. This is necessary for effective collaboration and co-production [178], which will facilitate the emergence of new socio-technical polycentric configurations for micro-generation, the allocation of space for DES infrastructures, the organization of management, and the establishment of efficient internal energy management systems within MG communities [113,179].

The resulting system's diversity and flexibility embody the original

SG concept as an adaptive, complex multi-level resilient resource system [196]. The hybrid grid, comprising substantial DES in MGs supported by larger-scale public grids, should evolve into a highly complex resilient system with strong adaptive capacity. It combines technical and social innovation and represents crucial institutional transformations [18] in the STS of electricity supply [180]. The necessary institutional transformations entail governing and managing the grid in a polycentric manner, which is key to enhancing robustness [126]. The identified contradictions in the SG paradigms strongly highlight the acknowledged or unacknowledged significance of control over the new infrastructures at the MG level. Similar to other RE infrastructures, the elements of the SmartGrid (SG) bring forth novel approaches and regulations regarding the ownership and control of energy flows and capacities. The institutional changes that underpin the establishment of these "social licenses" to operate [94,197] are crucial for ensuring legitimacy, community acceptance, trust, and justice, and hence, they are also vital for the energy transition [15,177,198].

Although the concept of renewable energy communities (REC), seems very suitable for SG conceptualizations emphasizing DES within MGs, the social-scientific literature on community energy has largely overlooked the physical systems of SG, RE), and MGs [199]. This omission in the attention to the physics of electricity supply systems is a significant bottleneck in addressing multidisciplinary issues and pooling expertise for joint problem framing [200].

The conclusions regarding bias in different disciplinary approaches also highlight a concerning issue in energy research: the absence of conceptual rigor. It has been observed that the domain of SG has become indistinct and lacking in clarity. However, it is important to note that this does not imply academic acceptance of amorphous concept formation. When fuzzy concepts are utilized as inputs, it also generates a lack of methodological rigor [201,202].

In addition to the need for improving fundamental understanding and academic relevance, the practical implications are equally troubling [201]. Contradictory conceptualizations among experts may exclude each other in implementation processes. Consequently, the ambitious expectations SGs to effectively address the challenges of current power supply systems by being adaptive and resilient [4,34] are likely to remain unfulfilled and may be perceived as a "smart utopia" [71,89]. These conceptual contradictions among experts in the field indicate conflicts in the implementation of SGs, which hinder the crucial development of RE sources. In addition to the disturbing phenomenon that RE has so far barely replaced existing energy use, but has indeed mainly been added to continuous operating base-load [203], the transition is in danger of being further delayed. This is concerning considering the urgency of transforming electricity grids into systems that provide carbon-free electricity, as well as the need for rapid RE implementation. Crucial is opening-up the central, hierarchical, highly standardized grid, particularly to foster the enormous variation in emerging microgrid architectures [204,205].

Slow deployment not only increases CO_2 emissions during the transition but also incurs higher costs for adapting the energy system [206]. The identified contradictions reflect the competing interests associated with established powers in existing grid infrastructures and their entrenched system lock-ins on the one hand, and actors challenging those powers on the other hand. Decisions regarding grid design can perpetuate existing lock-ins in infrastructure development, which can have implications for future generations [207]. This study has demonstrated that the concept of SG has multiple interpretations that are incompatible. Challenging the dominant centralist-hierarchical paradigm in electricity supply is an essential aspect of the original idea behind SGs.

Ethics statement

For this research, the Ethics Review of the AISSR research institute at the University of Amsterdam was followed. Two specific issues outlined in the review were taken into consideration:

- "Your research might have a direct impact on the lives of your research informants (e.g., because their life world is interfered with; it may be dangerous for them to work with you; their privacy is at stake)."
- "Your research is situated in fields of clashing interests (between e.g., an institution and its clients, governing bodies and groups being governed, industry and activists, and so on) that deserve to be handled with care".

The following strategy was implemented to address these issues. Prior consent was obtained from all respondents, ensuring their agreement to participate in the research. Respondents were recruited globally, including individuals from countries with autocratic regimes and employees of companies with strategic interests that prioritize confidentiality. Given the potentially sensitive nature of expressing views on energy system transformations, disclosing personal opinions can carry risks for the participating experts. To maintain complete confidentiality, all data collected were managed, processed, stored, and analyzed offline, excluding any cloud or server accessible to entities other than the researcher. Informed consent was obtained from all participants, with the assurance of complete anonymization in reporting. To protect anonymity, all data published in the supplementary material were pseudonymized, and no further additional information can be provided to anyone. All individual data and information that could potentially be used to identify individuals were carefully removed both from the data itself and from this publication.

CRediT authorship contribution statement

Maarten Wolsink: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The author declares no conflict of interests.

Data availability

Data have been uploaded as Suppl.Material; 3 data sets as sheets in one Excel file

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Appendix A. Supplementary data

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