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Review

Social arrangements, technical designs and impacts of energy communities: A review

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A B S T R A C T

Due to the potential for deploying distributed generation, improving energy efficiency and adopting sustainable energy-related practices, consumers provide significant value in the energy sector transformation. If their interests and goals are similar, they can group together and form energy communities. Energy communities enable consumers to jointly pursue their individual and collective economic, environmental and social goals, while simultaneously contributing to the decarbonisation of the energy system. Considering the growing interest in this field, this paper aims to enhance the understanding of the social arrangements, the technical designs and the impacts of energy communities. The social arrangements of energy communities are discussed in relation to the different actors, their roles and interactions. Then, the paper reviews the technical aspects of designing various local energy systems, while taking into account the goals of energy community members and outside actors. The reviewed literature is benchmarked with respect to the methods, modelling objectives and the constraints used in the design process. Finally, the paper quantifies the economic, environmental, technical and social impacts of energy communities, reviews the numerical indicators used to quantify these impacts and provides a critical discussion of the findings. Based on the findings, future research directions are highlighted.

Contents

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Abbreviations

AC	Absorption chiller
BSS	Battery storage system
CAPEX	Investment costs
CHP	Cogeneration unit
DC	District cooling
DG	Diesel generator
DH	District heating
DHC	District heating and cooling
DSO	Distribution system operator
EC	Electric chiller
EE	Energy efficiency
ESS	Energy storage system
EV	Electric vehicle
FC	Fuel cell
GA	Genetic algorithm
GB	Gas boiler
GE	Gas engine
GSHP	Ground source heat pump
GTH	Geothermal
HP	Heat pump
HSS	Hydrogen storage system
ICT	Information and communication technologies
IEMD	Directive of the Internal Electricity Market
IRR	Internal rate of return
LCC	Life-cycle costs
LCOE	Levelized cost of electricity
LCOH	Levelized cost of heat
LP	Linear programming
LOLP	Loss of load probability
MIP	Mixed-integer programming
MILP	Mixed-integer linear programming
MIQP	Mixed-integer quadratic programming
NLP	Non-linear programming
NPV	Net present value
O&M	Operation and maintenance costs
OEM	On-site load matching
PSO	Particle swarm optimisation
PTES	Pit thermal energy storage
PV	Photovoltaic
PVT	Photovoltaic thermal hybrid collector
RED II	Recast of the Renewable Energy Directive
RMO	Radial movement optimisation
r	Discount rate
SCR	Self-consumption rate
SSR	Self-sufficiency rate
ST	Solar thermal collectors
STES	Seasonal thermal energy storage
TSS	Thermal storage system
WACC	Weighted average cost of capital
WT	Wind turbine

1. Introduction

Humankind has long acknowledged that coordinated action brings higher returns [1]. Being a *zoon politikon* species, its first communities were formed to harvest food, build shelter and protect its members from outside threats. Since then, it has developed a social contract through which it organises socio-political interactions, including those in the energy sector. Faced with the challenge of climate change, the energy sector is undergoing a transformation [2]. As part of this transformation, end consumers, once passive, are now encouraged to take an active role by reducing their demand, or by locally generating or storing energy. As with other aspects of society, communities have found through trial and error that more can be done in this regard when acting collectively. Energy community projects are the result of this notion [3].

There are over 3,500 energy communities in the European Union [4], and many more in other parts of the world, such as the United States [5], Australia [6], Canada and New Zealand [7]. Historically, energy communities have been set up as grassroots initiatives to accelerate the energy transition, while offering economic, environmental and social benefits to their members. As an alternative to existing energy practices [8], the success of energy communities depends not only on the degree to which their members meet their own goals, but also on the degree to which these goals are aligned with those of outside actors [9]. In Europe, it has been noted that a regulatory shift is taking place away from the feed-in mechanisms that provided financial certainty to energy communities in the past. This has incentivised energy communities to adapt and to consider more market-oriented designs [10]. In this new framework, the interactions between the different actors, which have interests that often conflict, introduce numerous challenges in terms of the design of the energy communities. Typical misalignments of interests are found between energy communities, on the one hand, and energy service providers, grid operators or governments, on the other [11].

To examine the degree to which these interactions are considered in the literature relating to the design of energy communities, this paper aims to address the following research questions:

- What are the underlying structures and interactions between actors associated with the formation and operation of energy communities?
- How are energy communities modelled in the literature on the optimal design of energy communities, considering the existence of multiple actors and their conflicting goals?
- How are the economic, environmental, technical and social impacts of energy communities quantified?

These research questions are addressed here based on a thorough review of the state-of-the-art literature on energy communities. In Section 2, an outline is given of the social arrangements, roles and interactions of energy community members, both inside and outside of the community. Based on this framework, Section 3 describes how the design of energy community projects is modelled in the literature, bearing in mind the different technologies and goals of energy communities, as well as their possible trade-offs. Numerical indicators are required in order to keep track of the impacts of energy communities, and the indicators used to quantify the economic, environmental, technical and social impacts are identified and classified in Section 4. This section also evaluates the reviewed literature based on these indicators, taking into consideration context-dependent circumstances. Finally, some possible directions for future research are offered.

2. Social arrangements, roles and interactions in energy communities

There have been various *mutations* of the term *energy community* in the literature, such as civic energy communities [12], sustainable energy communities [13], clean energy communities [14], sustainable communities [15], renewable energy communities [16] and low carbon communities [17]. This section aims to introduce the various actors in energy communities and to map their roles and interactions, both inside and outside of the community.

2.1. Actors in the energy community and their roles

An actor in an energy community may be a natural person (or household), a school or university, a non-governmental organisation, a public utility company, a business whose primary area of economic activity is not energy-related, a local authority, a municipality, etc. The roles assumed by these actors, however, depend on the local conditions and on the goals of the energy community. Fig. 1 provides a visual representation of the roles of actors in an energy community.

2.1.1. Consumer

A consumer is the beneficiary of an energy commodity or service provided by another actor. As such, although the consumer has not invested in and does not own energy generation and storage units, they may benefit from any or all of the three general forms (environmental, economic, social) by joining an energy community, as discussed in Subsection 3.1.

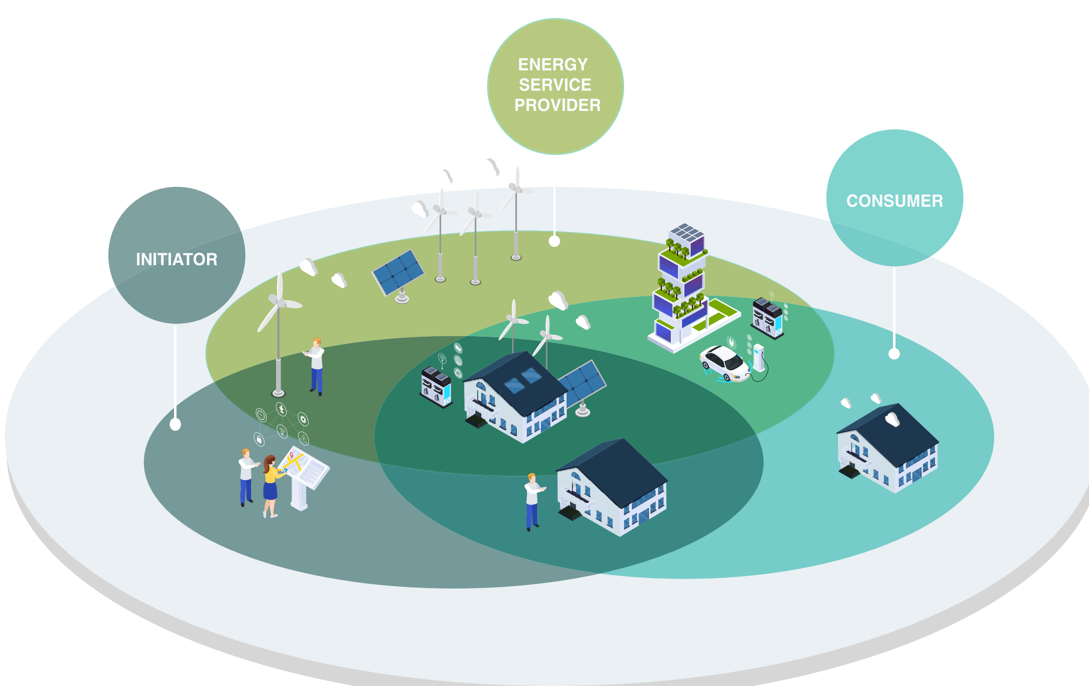

Fig. 1. Roles of actors in an energy community; an actor may take one or more roles in the energy community, as a consumer, energy services provider or initiator.

2.1.2. Energy service provider

The role of an energy service provider can be played by any actor that deals with the provision of an energy-related service, such as the generation, distribution, storage and supply of energy or energy-related commodities, and other energy services such as building refurbishment, the installation and maintenance of equipment, or aggregation. Energy service providers may own and use (either individually or collectively) infrastructure related to energy generation, distribution, storage and information and communication technologies (ICT). Generation and storage equipment may be located on site (e.g. rooftop generators, heat pumps) or nearby (e.g. district heating and cooling [18], seasonal heat storage [19], or local community-owned solar and wind generators [20]), or elsewhere (e.g. community-owned large-scale wind projects [1]). Since different types of actors may be energy service providers, this role should not be confused with a specific entity such as an energy service company (ESCO) or energy provider (i.e. energy supplier). Prosumers, for instance, can also act as energy service providers, since they fall at the intersection between *consumers* and *energy service providers*. Although they primarily generate energy for their own consumption, they can also share or trade energy with other community members through a peer-to-peer trading platform. Hence, prosumers act as energy service providers when they are net generators.

2.1.3. Initiator

Initiators are actors that set in motion the organisation or coordination of the community project. They play a crucial role in the energy community, as a lack of initiators may prevent the implementation of the project [21]. As actors in the community, they may or may not be beneficiaries of the community energy service. For example, the Centre for the Environment (CZZS) in Bosnia and Herzegovina helped initiate the 'Solarna Pecka' crowdfunding scheme for the installation of a renewable energy system at Visitor Centar Pecka. CZZS was not a direct beneficiary of the action; it simply helped Greenways, the organisation responsible for Visitor Centar Pecka, to obtain finance for solar, thermal and PV generators [22]. Similarly, the Sunny Roofs Cooperative in Serbia initiated the installation of a rooftop PV generator for a public utility company. The company will own the PV system and will repay the cooperative at a market price [22]. Consumers and prosumers can also act as initiators. An early example is the Solbyn association in Sweden, which formed a tenant-owned housing association in 1988. This housing association served as a legal representative in order to implement energy efficiency measures and invest in renewable heat for self-consumption [4]. In addition, consumers may receive aid from financing institutions and local governments, such as in the case of the hybrid energy system in Odhanturai, India [23]. They may also partner with local companies that have the resources to implement the project, as in the case of the Huatacondo microgrid project in Chile, where a local mining company has installed an energy system and will confer it on the community [23].

2.2. Interactions between actors in an energy community

The interplay between the actors in the energy community depends on the various features based on which each energy community can be classified. For example, the authors of [24] classify these communities based on their purpose (single or multi-purpose) and location (place-based or non-place-based). In terms of their organisation, energy communities may be centralised, decentralised or distributed [14], and can engage in various activities such as energy management, energy generation or self-consumption [12]. A detailed overview of the different legal entities that can be used to represent energy communities is provided in Ref. [4]. In Ref. [18], energy communities are classified based on their connection to the grid; for instance, a community that is connected to the power grid but deals behind the property lines of a housing company should not be subject to grid charges for energy that is generated and consumed behind these property lines. At the same time, energy communities with mutual power lines that run across property boundaries or that are distributed should pay network charges based on the general principles that apply to other consumers. Table 1 shows a number of features by which energy communities have been classified in the literature, each of which has a specific effect on the interactions between actors.

2.2.1. Organisation, structure and governance

The organisational and structural aspects of energy communities have been discussed in recent works, for example [4,23], and [26]. This subsection summarises the findings of these studies and cross-matches them with notable examples of existing energy communities.

The most basic form of an energy community is one comprised only of consumers. Such communities are formed with the aim of obtaining a collective discount (e.g. the Abbassa la bolletta initiative in Italy [8]) or with the aim of being aggregated for demand response [12]. Simple initiatives can easily be scaled up, as shown by the initiative of Abbassa la bolletta, where 60,000 participants took part in 2016. Consumer energy communities do not own or operate energy generation, distribution or storage units, although they may still pursue certain environmental goals by demanding to be supplied only with renewable electricity, as is the case for the energy cooperative Enercoop in France [4]. Consumers may also form coalitions with prosumers to buy their excess generation directly, for instance via a peer-to-peer trading scheme [14,27,28].

A common type of energy community is that consisted only of members that have collectively invested in a large-scale energy generation system (e.g. Gorran Highlanes, UK [8]). In the past, such energy communities have taken the form of energy cooperatives, limited partnerships or non-profit consumer-owned enterprises [4]. A survey in the US found that 90% of the respondents preferred '*their local wind project over a nuclear, coal or natural gas plant located at a similar distance*' [20]. Along with local wind farms, community solar photovoltaic cooperatives, in which actors jointly invest in a large-scale PV plant, are becoming increasingly

Table 1
Existing categories of energy communities in the literature.

Feature	Classification of energy communities	Ref.
Location and purpose	Single/multi-purpose; Place based/Non-place based	[24]
Organization	Centralized; Decentralised; Distributed	[14]
Activity	Energy management; Energy generation; Self-consumption.	[12]
Legal entity	Energy cooperatives; Limited partnerships; Community trusts and foundations; Housing associations; Nonprofit consumer-owned enterprises; Public private partnerships; Public utility company	[4]
Energy grid	On-grid/Off-grid; Within a housing company; Crossing property boundaries; Distributed energy community.	[4,25]

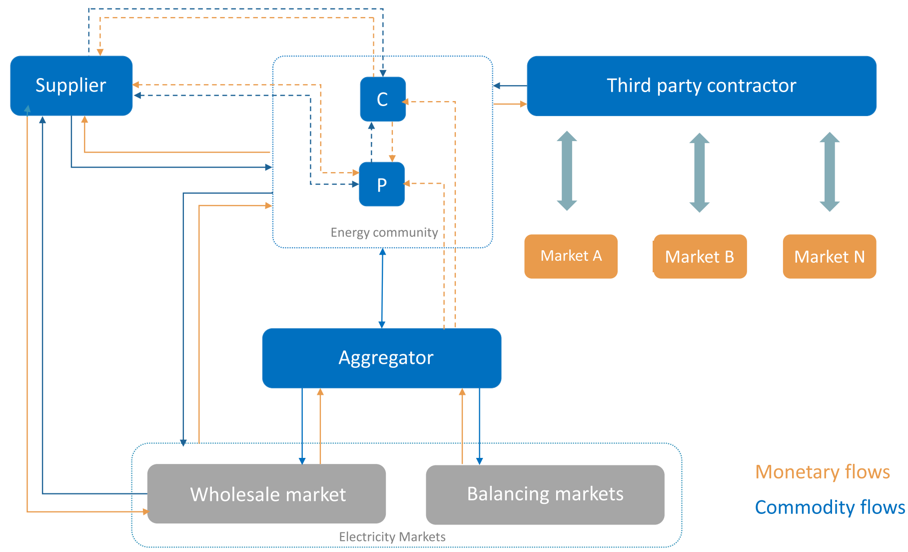

Fig. 2. Interplay between energy community with external actors; the energy community is represented only with one consumer and one prosumer for simplicity.

prominent [29]. There are about 3,500 such renewable energy co-operatives in Europe [4]. The advantages of centralised energy storage projects over decentralised projects are presented in Refs. [30–34]. This type of energy community was referred to as a centralised energy community in Ref. [14]. The prosumers in these communities may or may not be located on the premises of the community-owned energy infrastructure. In this respect, the energy community may be place-based or non-place-based, as per the classification used in Ref. [24].

Certain communities are formed with the aim of engaging in local self-consumption of energy (e.g. the Svalin co-housing complex [4]). The majority of the papers reviewed here fall into this category. These communities can be connected to the public distribution grid, but may also remain as isolated systems [35]. Isolated energy communities that focus on solar energy [36] tend to integrate flexible technologies, such as electric vehicles [37], in order to improve their self-consumption rates. On the other hand, grid-connected communities may comprise members from a single building or may cross property boundaries to form local microgrids [4]. Gui et al. [14] refer to these communities as decentralised communities. They can be organised as energy clusters, housing associations or energy cooperatives, among others [4]. Energy communities with district heating [19,38–44], district cooling [45–47] and both district heating and cooling networks [18,48] fall into this category. According to the recast of the Renewable Energy Directive (RED II) [49], these are examples of renewable energy communities, assuming that they do not use fossil fuels and that their members are in close proximity to each other. Communities engaged in PV sharing in multi-apartment buildings are also examples of renewable energy communities and renewables self-consumers. The works of Fina et al. [50–53] and Roberts et al. [32,54–56] are notable in this area. These communities usually jointly invest and own their energy system, although the system may also be owned and operated by a contracted third party [50].

A number of factors may restrict consumers and prosumers from taking part in local energy projects, such as a lack of available space for the installation of equipment. Other actors that own energy generation and storage units can, in this case, share a portion of their on-site generation with them. These communities have been referred to as distributed energy communities; they are usually non-place-based and connected with power lines that cross property boundries. A subset of such communities may take the form of virtual power plants that share energy via a peer-to-peer[1] (P2P) trading platform [14]. One example is the sonnenCommunity, developed by battery manufacturer sonnenBatteries, which enables citizens in Germany, Austria, Switzerland and Italy to become community members and share energy with each other without the need for a supplier [57].

2.3. External interactions of the energy community

Energy community members exchange information, energy and finance not only among themselves, but also with other actors outside the energy community. Fig. 2 shows a graphical representation of the relationships of an energy community with these external actors. For simplicity, the energy community is represented as having only one consumer (C) and one prosumer (P). Since we are analysing the external relationships of the energy community after it has been established, the initiators are not included in the figure. The monetary flows in the figure are shown by orange arrows, while the flows of services and commodities are depicted by blue arrows.

Energy communities should have the right to access any suitable market and should be treated '*on an equal footing*' with other actors in the energy sector, as stipulated in EU legislation [23]. This improves the likelihood of capturing the true value that the community can provide to its members and to the energy system [58]. An energy community can access a market directly, as a self-representative entity, or through a third party energy service provider such as an aggregator. Depending on the markets in which energy communities take part, they may bear a balancing responsibility. According to EU legislation, for instance, communities complying with the structure of renewable energy communities are not responsible for balancing, unlike the citizen energy communities introduced in the Directive of the Internal Electricity Market (IEMD) [59].

[1] Renewable Energy Directive, Art. 2 (18): 'peer-to-peer trading' is defined as 'the sale of renewable energy between market participants by means of a contract with pre-determined conditions governing the automated execution and settlement of the transaction, either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator. The right to conduct peer-to-peer trading shall be without prejudice to the rights and obligations of the parties involved as final customers, producers, suppliers or aggregators.'

When grouped as an energy community, individual members should retain their rights and obligations as individual actors (e.g. the right to change supplier) [60]. At the same time, they should also be able to act as a collective entity that can be connected at a single point of common coupling, for instance in the form of a microgrid [61]. The members of the energy community can later distribute their costs and benefits internally, based on a predetermined agreement. Finally, the energy community can hire a third party contractor to provide certain services [50], such as the purchase of fuel, installation, maintenance, etc.

2.4. Enabling factors

Energy communities are the social construct that facilitates cooperative energy projects. Their practical implementation, however, requires both non-technical and technical enabling factors to be in place.

2.4.1. Non-technical enabling factors

Non-technical enabling factors are found in environments that are rich with financial opportunities and have a proper legislative framework and active local initiators [10]. These aspects are required to compensate for the inability of the community to compete with market actors whose primary field of activity is related to energy. Even in communities with knowledgeable actors, community members can benefit greatly from simple institutional procedures and access to enabling financial opportunities and support schemes, since the impact of civil-led actions may be limited [62]. One can hardly expect every citizen of the community to put equal time and effort into its formation [21]; as noted in Ref. [63], it is more likely that a smaller set of actors, usually those with technical and financial knowledge, will spearhead the formation of the community. To ensure the success of renewable energy projects, governments of developed countries are expected to play only the role of an arbiter, whereas much more direct interaction is expected in developing countries [64]. Experience shows that the economic development of a country also affects the possible methods of securing reliable demand, subsidy models, risk guarantees and various revenue streams [65]. Knowledge drawn from examples of best practice, such as those highlighted by REScoop.eu [66], or the use of an over-the-counter information package, such as the PV-Gemeinschaft information site [67], can provide valuable guidelines. In line with this idea, the authors of [16] have found that the scaling up of energy communities can be aided by (i) generic rules and lessons at the system level; (ii) support from powerful actors; and (iii) heterogeneity in terms of actors, motivation and technologies.

2.4.2. Enabling technologies

Not all collective projects dealing with energy require an advanced technical infrastructure. Energy communities consisting solely of consumers, for instance, would require almost no enabling technologies if they were to seek a collective refurbishment or discount on an energy commodity. Access to a reliable power grid is a basic enabling technology; however, although energy communities in developed countries assume this infrastructure as given, grid access poses a more significant challenge in developing countries [65]. Energy communities in developed countries also tend to shift their focus towards the use of more advanced ICT infrastructure in addition to the basic energy infrastructure. These discrepancies are due to the differences in the development trends and focus of energy communities in different countries. In general, most technical architectures for the systems implemented by energy communities require enabling technologies in both the physical and virtual layers [68].

The basic technologies in the physical layer enable actors to generate energy locally (PV, wind, CHP) or to offer demand-side flexibility (via batteries, thermal storage, electric vehicles, or smart appliances) [11]. To share energy within the community, each actor requires a grid connection and an advanced metering infrastructure (AMI) [69] that includes smart meters, a network and a communication system. The smart metering infrastructure consists of advanced meter reading, time-of-use pricing and a data management system. Depending on the geographical span of the energy community, the communication network may be a neighbourhood area network (NAN) or a wide area network (WAN), in which each member has a separate home area network (HAN). Certain criteria for the latency, throughput, reliability and security of different elements in the communication network must be met, as noted in Ref. [70]. Finally, the virtual layer enforces the contracts and interactions discussed in Sections 2.2 and 2.3 of this paper. It consists of an information system (often enabled by ledger technologies [71]), market operation, pricing mechanisms and an energy management system, which controls the elements in the physical layer.

2.5. Barriers to energy communities

The actors in an energy community must individually and collectively overcome a number of challenges and barriers. Depending on their origin, these barriers may be either external or internal to the community [72].

External barriers are those which limit the community in terms of achieving its goals, and take the form of outside influences and forces. Technical, environmental and institutional barriers are typical examples. Technical barriers mostly result from the limitations of the distribution networks capacity. They arise and are emphasized by the intermittency of distributed renewable generation, the low energy efficiency of end users or the mismatch between local supply and demand [11]. The environmental barriers are related to the spatial requirements for the different technologies for energy generation [73], as well as to land use and waste [11]. As a result, technical and environmental barriers can result in a misalignment between the goals of the energy community and those of the outside actors, thus giving rise to numerous institutional barriers [9]. These institutional barriers may be manifested as a poorly defined legislative framework [54], a lack of institutional support or discrimination against small actors in the energy sector [5]. Institutional barriers may also be associated with structural resistance to grassroots initiatives (e.g. the prioritisation by local authorities of the development of a natural gas grid over district heating and cooling) or challenges related to demography and building stock [74]. Finally, Brummer noted a *saturation effect* that caused the interest in energy communities in Germany to fall over time, since all of the interested consumers were already part of energy communities or because the best locations for new energy community projects had already been taken [5]. However, this reduction in interest should be considered in conjunction with the elimination of favourable support mechanisms [10].

Internal barriers, on the other hand, are mostly socio-economic and organisational. The high investment cost of the infrastructure and the lack of access to finance are significant barriers. Moreover, a lack of initiative from local members has been recognised as a potential issue affecting the success of energy communities [21]; as noted in Ref. [21], '*The percentage of respondents willing to steer such systems, however, is rather small*'. A lack of expertise or a significant dependence on outside support can greatly reduce the resilience of energy communities [9]. Once such a community has been formed, its social and structural arrangements can highly influence its stability. A community is said to be stable if all of its members have no incentive to leave it or to form other communities. The manner in

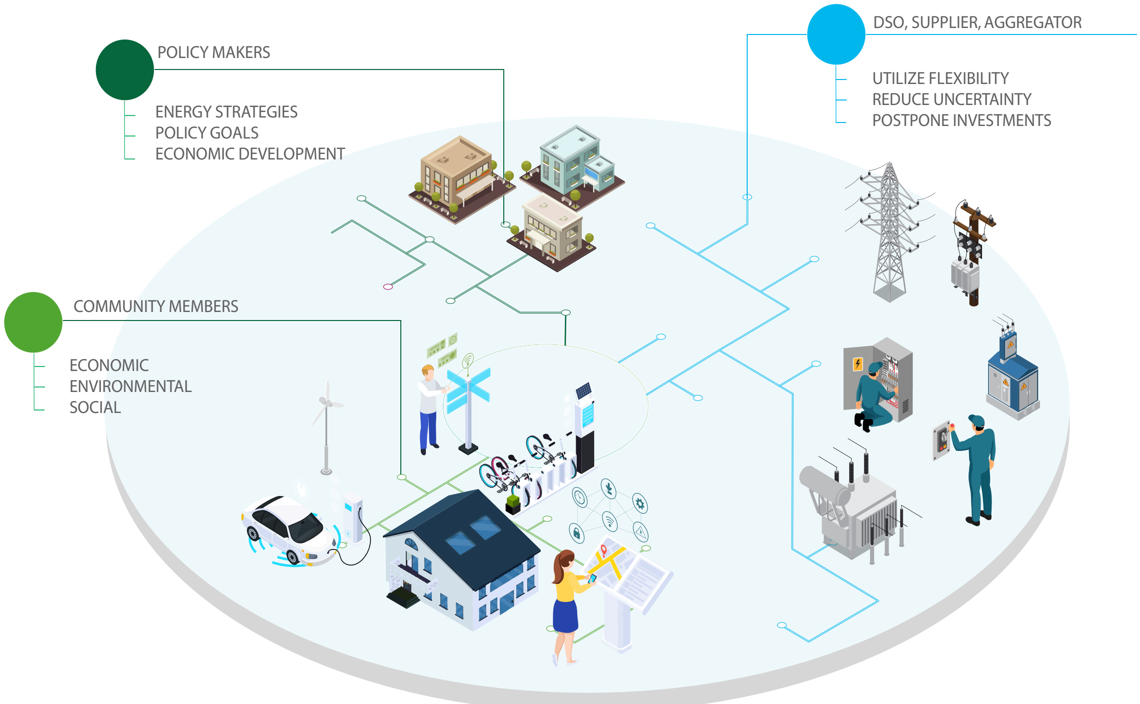

Fig. 3. Goals pursued by different stakeholders; the figure illustrates the different goals which stakeholders have that are related to energy communities.

which the gains are shared among members is one of the most dominant factors influencing the stability of the community; as discussed in Ref. [75], determining a fair and meritocratic mechanism through which value is shared within a community is not always a straightforward task. The interested reader is referred to Ref. [11] for a more detailed discussion of this topic, as well as topics related to other barriers.

3. Designing energy communities

The design of an energy community in terms of technology, structure and organisation constitutes a search or optimisation problem that aims to maximise the utility of the energy community while being subject to local technical and framework constraints [76].

3.1. Goals of energy communities

The utility of an energy community can be defined with respect to the goals of its members, while the framework constraints can be defined with respect to the goals of the external stakeholders, such as policy makers, DSOs, suppliers or aggregators, as shown in Fig. 3.

3.1.1. Goals of energy community members

Individual rationales for joining an energy community vary widely, but in general involve achieving certain environmental, economic or social goals. Although actors in society may pursue each of these goals independently, the literature shows there are a number of benefits in doing so collectively. For example, when grouped into an energy community, as opposed to acting individually, actors in society can reap benefits in a certain area simply by exploiting economies of scale (e.g. community battery storage vs. individual battery storage [34]), by gaining greater bargaining power (e.g. bulk buying of commodities [55]) or taking the opportunity to gain revenues from markets for which they would otherwise not qualify (e.g. from balancing markets through aggregation [77]). Following the classification of Brummer [5], we can also include *innovation* as an incidental benefit of energy communities, as this can have a spillover effect on the economy. In developing countries, the goals are more closely related to achieving basic electricity access or best practice for the deployment of renewable energy. Wealthier societies, on the other hand, are likely to have a lower degradation effect on the environment due to structural changes in their economic development [78]. As individuals become well-off, they are more likely to pursue environmental and societal goals and benefits, such as climate protection and fighting energy poverty [26]. Cross-matching between the benefits identified in Ref. [5] and the basic goals of energy community members is shown in Table 2.

3.1.2. Goals of other stakeholders

The formation of energy communities is influenced by conditions defined by other stakeholders. These stakeholders shape how energy communities can pursue their goals, but in a way that is in

Table 2
Goals of energy community members.

Goals	Brummer [5]
Environmental	climate protection and sustainability, renewable energy generation targets
Economic	economic, innovation
Social	education and acceptance, participation, community building and social realization

line with their own goals [79]. For policy makers, energy communities that use renewable energy facilitate the process of decarbonising, decentralising and democratising energy [6], thus contributing to national goals in relation to energy and climate. For profit-driven stakeholders such as energy suppliers and aggregators, energy communities offer additional revenue streams from different markets [77] by unlocking the flexibility of distributed deferrable loads, such as electric vehicles [80], or thermostatically controlled loads [81], such as heat pumps [82]. A review of 34 demand response projects shows that the technical challenges preventing the use of power-to-heat units to deal with generation and distribution capacity limitations are minor [83]. Since DSOs aim to provide a secure and reliable distribution of electricity to end-consumers, energy communities can offer benefits to DSOs by reducing violations of voltage and capacity limits [84]. Along with power-to-heat units, this can be achieved through the optimal location of storage units in the distribution grid [85] or by offering ancillary services (via community-owned storage [34] and demand-side flexibility [86]) that can be procured through a local flexibility market [87].

Nevertheless, rather than aligning with the goals of outside stakeholders, the goals of energy community members may also be in conflict with them [88]. For example, an energy community with local generation units might have interests that conflict with those of its suppliers (due to the revenue reduction caused), with non-community members (due to cross-subsidy benefits [89]) or with DSO (due to adverse impacts on the distribution grid [90–92]). The challenges related to these trade-offs are discussed in Subsection 3.3 and Section 5.

3.2. Modelling and design of energy community projects

The modelling and design of an energy system for energy communities can be approached as an optimisation problem, or through the simulation of multiple scenarios. A theoretical background and overview of both approaches is given in Ref. [93]. Four technology clusters were distinguished from a literature review: (i) shared solar PV systems, some of which include individual battery storage; (ii) community-owned storage; (iii) hybrid energy systems; and (iv) district heating and cooling, as shown in Table 3. Based on the discussion in the previous subsection, the approaches used for the design of local energy systems have been benchmarked in terms of their objectives and modelling constraints.

3.2.1. Modelling of the goals and desired impacts of the energy community

The goals and desired impacts of the energy community are translated into the *objectives* of the design problem. When the design is formulated as an optimisation problem, our review shows that regardless of the type of energy community, the economic goals are the dominant design objective, as shown in Fig. 4. The economic goals of the additional actors outside the energy community, such as third party energy service providers, are modelled in Refs. [35,50,104]. In general, the economic goals are represented using a cost function that includes the investment, operation and maintenance costs over the lifetime of the local energy system. To reduce the computational complexity, representative days are chosen for each month of the year. The authors of [61,110] proposed the use of machine learning algorithms, while in Ref. [111], a scenario reduction process was used for this purpose.

Table 3
Summary of different technologies for energy community projects.

Technology	References
Shared solar PV	[36,50–53,60,61,75,94–100]
Community-owned storage	[30–32,34]
Hybrid and multi-energy systems	[33,35,37,38,101–120]
District heating and cooling	[18,19,39–48]

The desired environmental impacts of energy communities were only considered in works dealing with hybrid and multi-energy systems (50%) or district heating and cooling (58%). In each type of paper, these environmental goals are considered alongside the economic goals of the community, and are modelled by including the environmental goals in the objective function, meaning that the optimisation problem becomes a multi-objective one [43,110,121], or by adding them as constraints to a single-objective optimisation problem [102]. The technical objectives of the local energy systems were considered in 42% of all of the references analysed here, most of which dealt with community-owned storage. Similar to the environmental objectives, the technical objectives were analysed alongside the economic objectives. Exceptions to this trend were noted in Ref. [95], which optimised only the capacity and location of the distributed PVs so that the losses and voltage deviations in the grid were reduced; in Ref. [107], which maximised the self-consumption of a community using a genetic algorithm; and in Ref. [108], which evaluated the potential of different design scenarios for the development of a self-sufficient community.

3.2.2. Modelling of local energy systems

Shared solar PV is one of the most common technologies applied by energy communities, due to its modularity and simplicity. From a modelling perspective, the framework constraints affect how the design problem is formulated. These framework constraints are related to the available billing mechanisms [122] and the possible technical PV arrangements that can be used by the community [55,60]. Most of the references reviewed here that applied heuristic methods to the design process used commercial software such as HOMER [36] or RETScreen [98]. Commercial software was also used to validate a case-specific optimisation model in Ref. [99]. As shown in Fig. 5, 60% of the studies dealing with shared solar PV considered the integration of behind-the-meter storage. To calculate the available rooftop area for larger communities, LiDAR images were used in Ref. [95]. The effects on the distribution grid were considered only in Refs. [61,95]; while [95] modelled the power flows [61], modelled the transformer loading at the substation level using a set of linear constraints. The rest of the papers in this category do not specifically focus on the grid interactions of the community, but assume that improving self-consumption offers economic benefits. They maximise self-consumption using storage units [36,51–53,60,61,96,97], demand response [100], and indirectly through heat electrification [50,51,53,60,94]. The thermal dynamics of the buildings considered in these papers are modelled using lumped element equivalent circuits. A disaggregated and systematic overview of these papers is given Table 9 in Annex A.

The orange bars in Fig. 5 give a summary of the constraints applied in those references that focus on community-owned storage. These works use simple battery models, based on the state of charge, charging and discharging efficiencies, and the power rating of the battery [31,32,34]. A linear battery ageing degradation model was presented in Ref. [30]. The authors highlighted the importance of considering the effects of ageing in the design, since they impact the optimal capacity, reducing it by between 6% and 92% compared to cases where ageing is not taken into account. The main contribution of these works is that they underline the advantage of community storage compared to individual storage units in terms of economics, reducing violations of voltage and current limits [31], improving self-consumption and reducing power exchange with the grid [32,34].

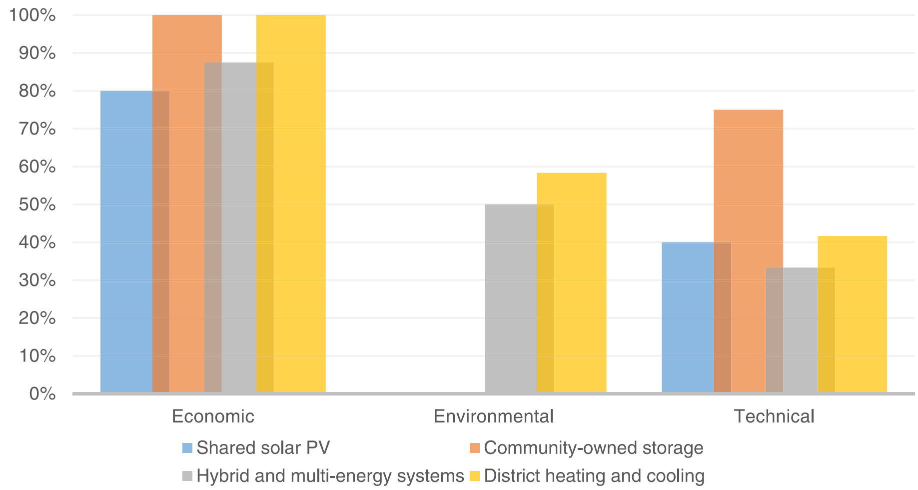

Fig. 4. Summary of the design objectives in the reviewed papers.

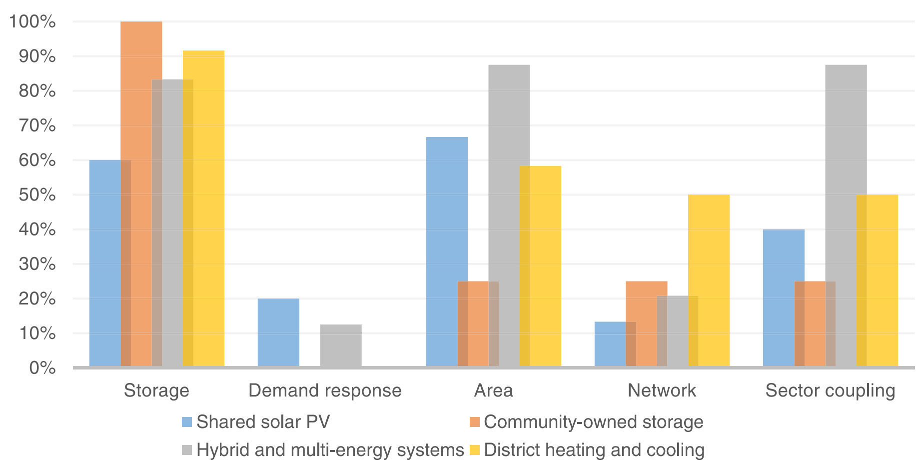

Fig. 5. Summary of the modelling constraints considered in the reviewed papers.

Table 4
Methods and modelling approaches.

Approach	Method	References
Heuristic	Individual model	[31–33,35,47,60]
	Commercial software	[36,40,42,47,98,99,106,108,112,115,120]
Mathematical programming	LP	[18,19,38,43,110]
	MILP	[19,30,34,41,46,50–53,61,94,102,103,105,110,111,116,117,119]
	MIQP	[75]
	MIP	[37,42,118]
	NLP	[99]
	DP	[45]
Metaheuristic	GA	[39,45,48,107,109,113,114]
	PSO	[95]
	RMO	[101]

The works on hybrid and multi-energy systems, represented by the grey bars in Fig. 5, address a wide array of technologies for electricity generation [37,101,105], multi-energy (electricity, heating and cooling) generation [102,113,116–119], as well as power and heat [33,38,107–110,112,115,118] and power and transport sector coupling [103,107,114,120]. Compared to the previous two categories of technologies, these works place greater emphasis on the environmental impacts of the community. From a modelling perspective, the districts are mostly represented by single-node models, and it is assumed that they are bounded in close geographical proximity. In this sense, the physical electricity and heat flows in the networks are not the primary focus of these works. When the networks are taken into account, this is achieved by imposing simple constraints on the maximum capacity flows or the energy losses [38,102,108,112,116]. References dealing with district heating and cooling systems were found to model the heat and mass flows in the networks more rigorously: for instance Ref. [46], describes an improvement in the solvability of the energy flows in a cooling grid [47]; models the steady-state mass flows in the grid; while [48] uses DYMOSIM for transient simulations.

As noted in Ref. [123], the main challenges of dealing with district-level energy models are related to the complexity of the model, the quality and uncertainty of the data, model integration, and policy relevance. Table 4 provides an overview of the modelling approaches used in the papers reviewed here, and classifies them as heuristic, mathematical optimisation or meta-heuristic approaches. There are many well-developed and widely used software tools that can be used for heuristic and scenario-based analyses, such as HOMER [36,106], RETScreen [98], TRNSYS [40,42,47,99,108], EnergyPlus [99], energyPRO [115], SimulationX-GreenCity [112] and EnergyPLAN [120]. *Open source* models have also been developed for the optimisation of the design of district energy systems, such as *rivus*, *urbs* [110], *Caliope* [111] and *modesto* [19]. Further information on these and similar software tools can be found in Refs. [124–126].

Mixed-integer linear programming (MILP) was the most frequently used optimisation method in our review. As in linear programming (LP) models, MILP models use linear constraints to represent the energy systems; however, they also use integer or binary variables to represent the operation and status of each element (on/off, charge/discharge) and investment decision (invest/do not invest). Other mathematical programming methods that were used included mixed-integer quadratic programming (MIQP) [75], mixed-integer programming (MIP) [37,42,118], non-linear programming (NLP) [99] and dynamic programming (DP) [45]. In the class of meta-heuristic algorithms, genetic algorithms (GA) [107] [39,45,48,109,113,114], particle swarm optimisation (PSO) [95] and radial movement optimisation (RMO) [101] were used. It is worth noting that the non-dominated sorting genetic algorithm II (NSGA-II) was repeatedly shown to be useful for dealing with multi-objective optimisation [39,48].

3.3. Trade-offs between security, affordability and sustainability

Investment in a low-carbon community project may not always be affordable to all members of the energy community; on the other hand, an affordable, low-carbon project may have adverse technical impacts on the distribution grid. There are several trade-offs such as these that must be considered in the design process of energy communities. Energy security, affordability and environmental sustainability are the three basic objectives used when designing and planning energy community projects. Approaches that also evaluate the social impacts have been proposed in Refs. [35,106]. Hence, being able to quantify the trade-offs between two or three of the goals of energy communities is valuable to both energy community members and other outside stakeholders when making investment or policy decisions.

3.3.1. Two-dimensional trade-off analysis

A two-dimensional analysis captures the trade-offs between two of the three factors in the security-affordability-sustainability trilemma. For example, trade-offs between economic and technical impacts were considered in the design of a fourth-generation district heating system in Ref. [19]. More specifically, the authors evaluated the trade-off between the primary energy share and the levelised cost of heat. Similarly, the study in Ref. [39] analysed the trade-offs between net electricity imports and life-cycle costs (LCC), while that in Ref. [36] analysed the trade-offs between reliability and investment costs. The reliability of the energy supply is a key factor when designing energy community projects for developing countries; however, energy autonomy comes at a higher economic cost, which may be challenging for low-income community members. The trade-off between the economic and environmental impacts is also of interest, and can be modelled as a multi-objective optimisation problem [38,43].

In multi-objective formulations, the set of all optimal solutions for different weights of the objective functions constitutes the Pareto front [110]. As shown in Fig. 6, the Pareto front reflects the relationship between the two conflicting objectives [38], and enables decision makers to evaluate the trade-offs between different approaches. Plotting the relevant indicators on a two-dimensional plane gives a visual representation of the possible effects of different planning preferences.

3.3.2. Three-dimensional trade-off analysis

Whereas a Pareto front shows the relationship between two variables, a radar plot can be used to evaluate a three-dimensional trade-off, i.e. a trade-off between three objectives. As illustrated in Fig. 6, each node of the radar plot represents the score for the economic, environmental or technical impacts of the system. The score for each node is calculated as a combination of metrics and indicators. For example, the authors of [121] used an energy trilemma index similar to that used by the World Energy Council to benchmark energy security based on the loss of power supply probability (LPSP) and excess generation. For the affordability, they used the life-cycle costs and the levelised cost of electricity (LCOE). Finally, they used the life-cycle CO_2 emissions and the renewable energy share to score the environmental sustainability aspect of the system. A similar approach can be found in Ref. [113], in which the authors compared the benefits of an integrated multi-energy

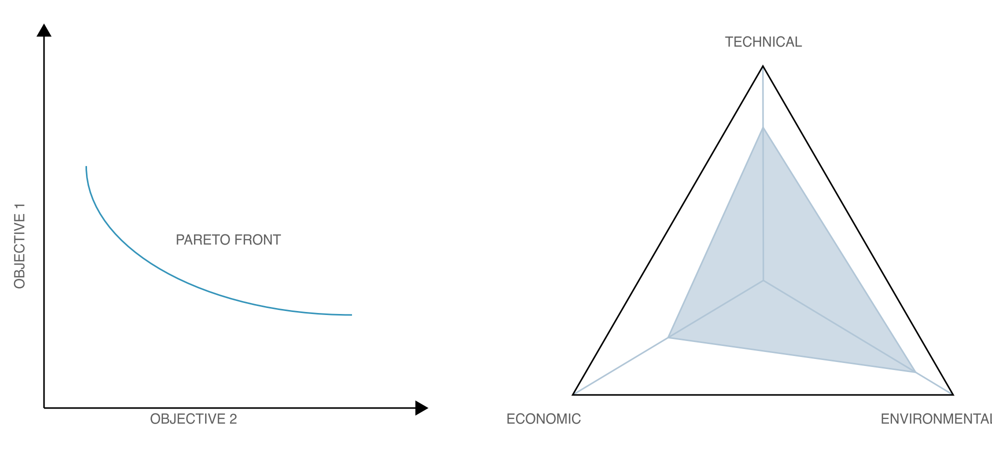

Fig. 6. Graphical representation of a) two-dimensional trade-off analysis and b) three-dimensional trade-off analysis.

Table 5
Indicators used to quantify the impacts of energy communities.

Impact	Indicators
Economic	Energy bill savings; Investment; Operation and total cost savings; Levelized cost of energy; Internal rate of return (IRR); Payback period; Life cycle cost; Net-present value.
Environmental	GHG; CO2; Life-cycle emission; Refrigerant emission, Particulate matter.
Technical	Self-consumption ratio (SCR); Self-sufficiency ratio (SSR); Loss-of-load probability (LOLP); Load match index (LM); Electricity exports; Primary energy.
Social	Public acceptance (PA); Human development index (HDI); Health issues (HI); Universal education and gender equality (UE); Creation of jobs (COJ)

system, albeit using different indicators. Of the studies reviewed here, neither of the frameworks (two-dimensional or three-dimensional trade-off analysis) was used to focus on trade-offs with social impacts.

4. Quantifying the impacts of energy communities

Energy communities currently play only a small part in the wider context of energy systems, and the burden of proof regarding their impacts and benefits therefore falls on existing field projects

Table 6
Overview of economic impact of community energy projects or energy systems suitable for community energy projects.

Ref.	Technology	Indicator	Economic impact	Discounting factor	Lifetime
[30]	PV, battery microgrid	Energy bill savings	Not considering battery ageing overestimates costs savings by 5−12%	n.a.	n.a.
[36]	PV, BSS	Energy bill savings	2% electricity shortage can reduce electricity bills by 20% in isolated systems	$r = 0\%$	not specified
[51]	PV, BSS	Energy bill savings	Rural single family houses can benefit more than other dwelling (additional 5% cost reduction by participating in an energy community)	$r = 3\%$	20 years
[52]	PV, BSS	Energy bill savings	Austria: 90 EUR/year building costs savings (23% SCR); Germany: about 970 EUR/year building costs savings	WACC = {3,5,10}%	not given
[53]	PV, HP, NG, DH	Energy bill savings	Cost reduction of 45% when heat load is reduced from 160 kWh/m^2/year to 60 kWh/m^2/year	$r = 3\%$	20 years
[60]	PV, BSS	Energy bill savings	Annual building level saving of 437.29 EUR/year with an energy community; 50% PV capacity more than the no energy community scenario	n.a.	n.a.
[96]	PV, BSS	Energy bill savings	Household increased payoff by 34.20 $/year when in community	$r = 6\%$	10 years and 15 years
[101]	WT, PV, BSS	Energy bill savings	16.7% increase in annual costs observed	n.a.	n.a.
[104]	PV, GSHP	Energy bill savings	Annual operational costs savings 7 $/person-year	$r = 3\%$	13−63 years, different technologies and assumptions
[18]	EC, AC, PTES, BSS, CHP, HSS, EC, GTH	Total cost savings	Socio-economic cost decline for district cooling share up to 30%	$r = 4\%$	not given
[38]	PV, CHP, HP, ESS, TSS, GB;	Total cost, investment cost and operation cost savings	Total cost reduction - 24%; Investment cost reduction - 26.4%; Operation cost reduction − 17.6%	n.a.	n.a.
[41]	CHP, HP	Total cost savings	30% CO2 reduction − 11.5% increase in total costs (investment + O&M) 40% CO2 reduction − 22.0% increase in total costs (investment + O&M)	$r = 3.5\%$	15 years for supply technologies, 30 years for grids
[103]	PV, FC, CHP, EV, TSS, GB	Total cost savings	12% cost reduction of controlled vs. uncontrolled EV charging	not given	not given
[110]	PV, HP	Total cost savings	Introduction of an energy community model reduced total costs by 32%	WACC = 2%	18−25 years for supply technologies, 40 years for grids
[114]	PV, GB, BSS, TSS, FC	Total cost savings	About 25% reduction in the total cost of ownership	$r = 0.05\%$	not given
[117]	PV, CHP, GB, BSS, TSS	Total cost savings	Investment of 1325 EUR/year reduces costs by 89% (Pareto analysis)	$r = 7.5\%$	20 years
[102]	PV, AC, EC, GE, ESS, TSS	Investment cost savings	33% reduction in chiller size	not given	20 years
[119]	AC, EC PVT, DG, ESS	Operation cost savings	Cost savings of about 0.08%−16% in four buildings	$r = 8\%$	25 years
[19]	GTH, HP, excess heat	Levelized cost of energy	LCOH: 0.045 EUR/kWh for 25.0% primary energy import share; LCOH: 0.031 EUR/kWh for 35.5% primary energy import share	$r = 3\%$	20−30 years
[40]	ST, STES, HP, DH network	Levelized cost of energy, Payback period	14% lower LCOH for proposed than gas fired boiler. Payback period 6 years. Benefit-cost ratio 1.7.	$r = 5\%$	15 years
[106]	WT, PV, BSS, EE	Levelized cost of energy	22% reduction in the $/kWh cost of energy of the system compared to existing system	$r = 5.88\%$	25 years
[33]	HP, chiller, TSS	IRR	IRR (30-year unlevered after-tax) 11.9%	depreciation rate 9.5%	30 years
[34]	PV, battery	IRR	IRR in communities with individual. storage - 8.0% IRR in communities with collective storage - 9.3%	$r = 5\%$	n.a.
[47]	EC, HP, TSS	IRR	IRR (30 years) is 4.1%; ROI is 21.9%	$r = 2.5\%$	30 years
[97]	PV, BSS	Payback period	Payback period of 12 years	$r = 6\%$	20 years
[116]	PV, HP, FC, waste boiler, CO2 storage, CH4 storage	Payback period	900-1300 EUR/cap investment would yield in a 11−14 year payback period	$r = 8\%$	20 years
[39]	PV, WT, BSS, EV	Life cycle cost	Specific life cycle cost increase from 534 EUR/m^2 to 1190 EUR/m^2, 764 EUR/m^2 or 585 EUR EUR/m^2 for 97%, 58% and 16% onsite energy fraction.	$r = 3\%$	25 years
[113]	PV, ST, CHP, EC, TSS, back-up boilers	NPV	55 MEUR NPV at the end of project lifetime	$r = 4\%$	25 years

Table 7
Overview of emissions reduction in the reviewed literature.

. Ref.	Technology	Emission type	Emissions reduction
[33]	HP, CHP, TSS	GHG emissions	multi-unit residential buildings: 53–84%; data center: 51–82%,
[38]	PV, CHP, HP, BSS, TSS, GB	GHG emissions	53.6%
[40]	ST, STES, HP, DH network	GHG emissions	<61%
[101]	WT, PV, BSS	GHG emissions, Particulate matter	37.6%
[47]	CH, HP, TSS.	CO2 emissions; Refrigirant emissions	21–46% CO2; 34% refrigerant emissions reduction
[106]	WT, PV, BSS, EE	CO2 emissions	54%
[110]	PV, HP	CO2 emissions	85%
[112]	PV, WT, HP, BSS, TSS	CO2 emissions	3,000 tCO2/year
[113]	PV, ST, CHP, EC, TSS, back-up boilers	CO2 emissions	12,593 tCO2/year
[117]	PV, CHP, GB, BSS, TSS	CO2 emissions	<61%
[48]	EH, HP, CHP	Life cycle emissions	6.02 to 15.25 $kgCO_2$-eq/m^2/year
[104]	PV, GSHP	Life cycle emissions; CO2 emissions	Overall life cycle impacts reduced by 11.4%; annual CO_2 emissions reduced by 21.70%.

and the scientific works in the literature. These impacts and benefits should be clearly reported. The added value and additional costs arising from energy communities should be obtained through comparison with scenarios in which no energy communities are formed. This section aims to identify and classify the indicators used to evaluate the economic, environmental, technical and social impacts of energy communities, as reported in the recent literature. A summary of these indicators is given in Table 5.

4.1. Economic impacts

With little uniformity, the economic impacts of community energy projects can be assessed in terms of:

- Energy bill savings [30,36,51–53,60,96,101,104],
- Investment, operation and total cost savings [18,38,41,102,103,110,114,117,119],
- Levelized cost of energy [19,40,106],
- Internal rate of return (IRR) [33,34,47],
- Payback period [40,97,116],
- Life cycle cost [39],
- Net-present value [113].

The economic impact of these projects is measured in comparison to a business-as-usual reference scenario. The most valuable comparisons are those which provide insight into the added value of participating in an energy community using numerical indicators. Some indicators, however, are affected by the economic assumptions made for the discounting factors (the discount rate *r*, weighted average cost of capital (WACC) or depreciation rate) and the lifetime of the project. Table 6 reviews the economic impacts reported in the papers reviewed here based on the indicators identified above, together with the assumptions made in each, so that the case- or context-dependent circumstances can be considered. The projects in Table 6 are classified based on the indicators mentioned in Table 5.

4.1.1. Consumer-centric economic indicators

Many references use energy bill savings, a fairly intuitive indicator, to describe the economic performance of investments in shared solar and hybrid microgrids, as can be seen in Table 6. The results show that for investments in PVs, community systems and energy sharing can outperform individual systems [75]. In general, the economic performance of shared PV systems in multi-apartment buildings increases when electricity tariffs are higher

Table 8
Overview of technical impact of energy community systems.

Ref.	Technology	Indicator	Focus	Result
[52]	PV, BSS	SCR	Cost savings – autonomy tradeoff	SCR ≈ 15–45% (w/o storage) SCR ≈ 35–65% (w/storage)
[56]	PV	SCR	Self-consumption	SCR ≈ 29–39% (not affected if more than 10 households are aggregated)
[108]	PV, ST, TSS, HP	SCR	Self-consumption	70% of electricity is met with PV and efficiency measures
[104]	PV, GSHP	SSR	Load matching	SSR = 44%
[100]	PV, BSS	SSR	Self-sufficiency	SSR = 74% (w/o energy community) SSR = 100% (w/energy community)
[99]	PV, BSS	LM	Load matching	LM indicator ranges
[97]	PV, BSS	LOLP	Reliability improvement	0.4% LOLP
[32]	PV, BSS	SCR, SSR	Load matching and grid interaction	SCR ≈ 50–100%; SSR ≈ 0–50%; peak demand reduction of 30%;
[39]	PV, WT, BSS, EV	SCR, SSR, Electricity exports	Load matching and grid interaction	SCR = 62–76%; SSR = 1–58% (w/storage) SCR = 27–90%; SSR = 1–97% (w/o storage)
[107]	PV, EV, HP	SCR, SSR	Load matching	SCR = 86.1%; SSR = 20.3% (w/o energy sharing) SCR = 79.4%; SSR = 25.1% (w/energy sharing)
[112]	PV, WT, HP, BSS, TSS	SCR, SSR, LOLP	Load matching and reliability	SCR ≈ 57–73%; SSR ≈ 94–100%; LOLP ≈ 0.4–2.2%
[34]	BSS	Electricity exports	Reduce exports	64–94% lower grid exports when using shared storage as opposed to individual storage
[31]	PV, BSS	Electricity exports	Reduce exports	by 67% with individual batteries by 94% with shared batteries
[40]	ST, STES, HP, DH heating network	Primary energy	Primary energy saving	Up to 73% (compared to gas boiler scenario)
[102]	PV, AC, EC, GE, ESS, TSS	Primary energy	Primary energy reduction	10% and 20% (endogenous parameter)
[113]	PV, ST, CHP, EC, TSS, back-up boilers	Primary energy	Primary energy saving	5,700 toe/year
[19]	GTH, HP, excess heat	Primary energy	Cost-autonomy trade-off	Pareto front analysis (LCOH vs. primary energy import share)

[52]. Multi-apartment residential buildings with PVs or PVs with batteries have been shown to save up to 90 EUR/year in Austria, 970 EUR/year in Germany [52] and 437.29 EUR/year in Finland [60]. Further economic potential also lies in the exploitation of the synergy between PVs and heat pumps [53]. The authors of [104] note that energy communities with PVs and ground-source heat pumps yield cost reductions of 7 $/person-year. The magnitude of these savings is not universal, and depends on local electricity tariffs, legislation and the size of the system. The authors of [51] found that separate rural single-family homes in Austria could save an additional 5% on their energy bills when participating in PV energy communities, while the savings made by households with PVs and batteries in Western Massachusetts were around 34.20 $/year [96]. With regard to storage, the authors of both [32,34] argue that community systems outperform individual ones.

As shown by the cost savings on the energy bills in the references mentioned above, the reported benefits are limited. However, it should be noted that the implementation of distributed energy such as PVs, either in multi-apartment buildings or other systems, can sometimes be more easily achieved collectively than individually. This could be a suitable measure for empowering end-users [26]. In the case of multi-apartment buildings, shared PVs make use of a rooftop area that would otherwise remain unused, which is a further added value worth considering.

4.1.2. Investor-centric economic indicators

Some works have reported the economic performance based on the total costs, comprising the investment costs [102], operation costs [119] and other costs such as those from environmental taxes. These indicators are much more useful for the stakeholders investing in the energy community infrastructure and operating the energy systems. The results show that by forming an energy community, the total cost associated with investment, operation and maintenance can be reduced by about one third [110]. Similar results were found in Ref. [38], where the total cost was reduced by 28%; in Ref. [18], where the socio-economic costs were reduced by 30%; and in Ref. [114], where the total cost of ownership was reduced by 25%. Nevertheless, it is clearly noted in Ref. [41] that there is a trade-off between the total cost and the environmental impacts, i.e. lower environmental impacts reduce the cost savings.

Finally, the economic performance of energy community projects has also been reported based on indicators more typically used in project planning, such as NPV [113], payback period [40,97,116] and IRR [33,34,47]. The results show that the payback period of district heating systems can be as low as six years [40]. Other works have found payback periods of 12 years for PV and storage projects [97], while the payback periods of more complex systems are in the range 11–14 years [116]. The reported IRRs range from 4.1% in Ref. [47] to 11.9% in Ref. [33]. The relationships between the life-cycle costs and the self-consumption are discussed in Ref. [39], as shown in Table 6 with the findings on the levelised cost of energy [19,40,106]. These results show that optimal sizing and comprehensive scenario analysis can significantly improve the economic performance of energy systems.

4.2. Environmental impact

Environmental concerns are among the most potent factors influencing a consumer's willingness to participate in an energy community project [21]. As shown in Table 7, the papers reviewed here reported environmental impacts on the basis of:

- GHG emissions [33,38,40,101],
- CO_2 emissions [47,106,110,112,113,117],
- Life-cycle emission [48,104],
- Refrigerant emission [47],
- Particulate matter [101].

The overall GHG emissions are associated with emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2), and refrigerant gases such as chlorofluorocarbons and hydrochlorofluorocarbons. The GHG emissions can be analysed by considering each GHG separately, as in Ref. [33], or by using a CO_2-equivalent emission factor that combines the impacts of all GHGs into a single quantity, as in Refs. [38,40,101]. The results show that when an optimal hybrid or multi-energy system is installed, the GHG emissions can be reduced by 37.6–84% depending on the reference system and the technologies used. Similarly, the authors of [47] report that for a district cooling system supplying 26 GWh of cooling to a tourist area, the CO_2 emissions could be reduced by 21–46%, while the refrigerant emissions could be reduced by 34%. Reductions in CO_2 emissions within a similar range were also found in Ref. [106], although the environmental benefits were achieved by implementing energy efficiency measures and battery storage together with the implementation of wind turbines and PVs. The authors of [117] found that including storage in net zero energy communities reduced the emissions by 60% in comparison to a case without storage.

Substituting fossil fuel-based heating with PVs and heat pumps can provide significant environmental benefits. For a case in Linz, Austria, the authors of [110] found that PVs and heat pumps could reduce CO_2 emissions by as much as 85%. However, this would increase the total cost by a factor of six due to infrastructure investments; as a result a system of a different size would be more cost-effective. For example, a cost-optimal solution involving PVs and ground-source heat pumps for a multi-apartment residential building in British Columbia, Canada, could reduce emissions by 21.70% [104], while the overall life-cycle impact of the same system was reduced by 11.4%. The life-cycle emissions reflect the GHG emissions calculated using a life-cycle assessment. In Ref. [104], the authors used a life-cycle approach that included uncertainty considerations. In contrast, the life-cycle assessment reported in Ref. [48] calculated the life-cycle emissions based on the EN 15804 standard.

Some papers have reported absolute reductions in emissions without providing a business-as-usual scenario that would allow a comparison to be made, and in these cases it is difficult to put the reported emission reductions into context. For instance, in Ref. [112], it was found that a hybrid microgrid could reduce the CO_2 emissions of a rural Siberian community by 3,000 tCO2/year. The paper reports the total energy demand of the community and the emissions factor of the energy system, but lacks a calculation of the relative emission reductions as a percentage. The results in Ref. [113] are similar, as they provide a reduction in emissions in absolute terms (12,593 tCO2/year), but do not provide a reference value that can be used to evaluate the relative reduction.

The environmental indicators found in the reviewed literature are by no means exhaustive. For example, of all the papers reviewed here, only one [101] focused on local air pollution, despite this being a problem for many communities. It was also the only paper found in our review that considered the change in the grid emission factor in the outside energy system over time. The studies reviewed here did not evaluate the embodied emissions, and a diversity of reference systems were used to calculate the emission reductions. With this in mind, greater transparency in and justification of the choice of the reference case is required in future research, as well as a more holistic analysis of the relevant emissions.

4.3. Technical impact

Collective energy projects improve the autonomy, increase the reliability and reduce the overall energy consumption of communities, as shown in Table 8. The indicators used to discuss the technical impacts of local energy projects are:

- Self-consumption rate (SCR) [32,39,52,56,107,108,112],
- Self-sufficiency rate (SSR) [32,39,100,104,107,112],
- Loss-of-load probability (LOLP) [97,112],
- Load match index (LM) [99],
- Electricity exports [31,34],
- Primary energy [19,40,102,113].

SCR, SSR, LOLP and LM are four of the load-matching and grid interaction indicators that were primarily developed for the analysis of net zero energy buildings (NZEB) [127,128]. As shown by our review, they have also been extensively used for the technical evaluation of energy community projects. More specifically, Bentley et al. [129] used SCR and SSR to discuss energy autonomy at various levels. Their review covers the challenges and opportunities for energy autonomy, while offering insight into the economic and environmental impacts that arise from energy autonomy.

In our review, we found that supplying the aggregate load of the community with a collective generation unit (or shared distributed generation units), as opposed to supplying individual loads with individual systems, yields better load-matching indicators and lower grid impacts [130]. This has been substantiated by an analysis of a case in Australia [56], which highlighted that the SCR of households with PVs ranged between 29% and 39%. Interestingly, this indicator does not significantly increase when more than 10 households are aggregated. Enabling households to share energy with each other can improve their load-matching capabilities in terms of the share of locally supplied demand (SSR) [104] and the on-site energy matching (OEM) [39]. For instance, in Ref. [100], it was shown that an NZEB microgrid approach increased the SSR by as much as 26%.

Studies in the literature have repeatedly shown that load matching and reliability can be significantly improved using batteries, as shown through the use of SCR [52], LM [99] and LOLP [97]. However, recent works show that shared batteries outperform individual batteries, as they can help integrate larger PV shares (up to 27.5% in the case of [107]), improve self-sufficiency, lower peak demand [32] and lower electricity exports to the grid [31,34]. Hybrid energy systems have diversified generation profiles and greater energy flexibility, which can be used to further improve the autonomy of energy communities [112] and reduce primary energy demand [113].

When sharing energy, the members of a community act as energy hubs that are simultaneously both consumers and providers of energy services, and can therefore offer flexibility to different energy markets, either locally, peer-to-peer [68] or via an aggregator [77]. The distributed nature of peer-to-peer energy sharing has motivated some researchers to compare it to the Internet, although the two differ in many respects, as noted in Ref. [131]. The main difference is that unlike the Internet, the physical energy that flows in the grid can hardly be routed, and may not follow the monetary transactions between members [132]. As a result, this mode of operation introduces challenges to the operation of the distribution grid. To overcome these challenges, screening approaches have been proposed, such as the '*traffic light system*' enforced by the DSO to approve demand response actions [133].

5. Social impacts

In general, the studies of energy communities reviewed here lacked a quantitative framework for evaluating the social impacts and benefits. Among these benefits are enhanced social cohesion, improved energy literacy, the development of social networks, the promotion of global partnerships and reduced energy poverty [6,134–136]. Of the reviewed papers, only [35,106] included the social aspect in the design process. The authors of [35] proposes the use of the following key performance indices: public acceptance, human development index, health issues, universal education and gender equality, and the creation of jobs. Although the study in Ref. [106] provided a list of important social criteria, no method was offered for their quantification. In both papers, the social impacts were not evaluated with the quantitative rigour applied to the evaluation of the economic, environmental and technical impacts. From the existing literature, a number of approaches can be found that can be used to fill this research gap. An overview of methods for measuring the socioeconomic impacts of renewable energy projects was given in Ref. [137], while [138,139] discussed measures relevant to energy and fuel poverty.

5.1. Energy poverty

Community projects aiming to reduce energy poverty are intended for less developed communities, since about 1.3 billion people have no access to electricity (95% of Asia and sub-Saharan Africa) and 2.6 billion people rely on biomass for their basic energy needs [140]. Existing small-scale community projects have been shown to reduce energy expenditure, to improve the local economy and to provide better living conditions in developing countries [136].

Agrarian households in rural areas, for example, can couple PVs with modified irrigation systems to act as pumped hydro storage units to power the irrigation process, making it more efficient and less costly [141]. Microgrids can be deployed to electrify remote isolated villages in hilly areas [97] or in Arctic [142] and cold climates [112]. However, isolated systems face a trade-off between reliability and cost, in that lower costs lead to greater energy shortages [36]. It may therefore be difficult for a low-income community to obtain the necessary investment budget without an enabling financial and policy framework.

5.2. Fuel poverty

High upfront costs and uncertainty regarding cost-benefits may hinder the engagement of vulnerable consumers in community projects, not only in low-income countries but also in more affluent societies [26]. The European framework on energy communities defined in RED II and IEMD aims to provide an enabling framework for all consumers '*including those in low-income or vulnerable households*'. Hanke and Lowitzsch [26] suggest subsidising low-income households to join energy community projects, while avoiding harming their social welfare transfers. Unlike the literature on electrifying rural and isolated communities, our review identified little to no discussion of the ability of energy communities to alleviate fuel poverty. With 20% of households in the EU10 experiencing difficulty in keeping their home adequately warm [143], there may be significant room for improvement in this area.

6. Conclusion and future research challenges

This paper has reviewed the state-of-the-art literature on energy communities in order to evaluate the related economic, environmental, technical and social impacts, while considering the different possible technical and social arrangements. Initially, we identified the possible actors in energy communities and mapped their roles and interactions, both inside and outside of the community. Four particular types of energy communities were distinguished on the basis of the technologies used: (i) shared solar PV (rooftop or collective, with or without individual batteries); (ii) shared storage; (iii) multi- and hybrid energy systems; and (iv) district heating and cooling systems. When designing these communities, the goals of members are represented by the design objectives, while the framework defined by the outside stakeholders and the technologies applied impose constraints on the design problem. The reviewed papers were therefore benchmarked with respect to the objectives and the modelling approaches used in the literature on energy community design. Finally, we identified the indicators used to quantify the economic, environmental, technical and social impacts of energy community projects. Based on these indicators, we evaluated the impacts reported in the literature and discussed the associated trade-offs. In a wider context, this can help to inform decision makers of the possible benefits and challenges arising from supporting different energy community arrangements, allowing them to move closer to meeting national energy and climate goals.

A successful energy community design achieves a delicate balance between the goals and impacts of energy communities, and takes into account the relevant trade-offs and the conflicting interests of multiple stakeholders. Based on the conclusions of this review, we find that there is much work to be done in terms of exploring the following aspects:

1. *Coalition stability:* To ensure that the coalition of the energy community is stable, its members should have no incentive to leave it or to join other communities. Using game-theoretic models, peer-to-peer energy trading mechanisms or ex-ante pay-off allocation, the current literature focuses on developing consumer-centric pay-off distribution schemes that are based on the daily operational aspects of the community. To offer a more realistic pay-off distribution to community members, future research should adopt a holistic approach which also considers the non-operational aspects, such as the differences in investments, organisation, initiative and know-how provided to the community.
2. *Conflicting interests of different actors:* The present literature makes it clear that energy communities provide cost savings for their members. In a wider context, however, there is a risk associated with transferring these costs to other actors, such as DSOs and outside consumers. In view of this, research is needed to explore the different interactions between the energy community and outside actors. These interactions should define the market, technical and billing constraints that enable energy communities to co-exist with other actors in a fair manner that provides added value. This line of research could benefit from merging the design and operational aspects of energy communities, and should explore their synergies. Research is also needed to explore the role of energy communities in improving energy security and national environmental targets.
3. *Common framework for trade-off analysis:* One of the most significant challenges is the development and use of indicators to quantify the social impacts of energy communities. Although this review has discussed various indicators drawn from the relevant literature and has proposed possible ways of moving forward, there is much work to be done in this area. Social impact indicators can be used alongside economic, environmental and technical indicators to develop a common framework for multi-dimensional trade-off analysis of energy community impacts that will be valuable for community members, policy makers and investors.
4. *Evolution of investment opportunities and interests over time:* Most works dealing with energy community design consider the procurement of the energy infrastructure to be a single-stage event. However, experience shows that it is more common for energy communities to spread out their investments over time, based on annual savings, the development of local financial opportunities and the interests of the community. These temporal dynamics need to be taken into account in future research, especially when designing hybrid and multi-energy systems.

CRediT authorship contribution statement

Vladimir Z. Gjorgievski: Investigation, Methodology, Formal analysis, Writing - original draft. **Snezana Cundeva:** Methodology, Supervision, Writing - review & editing. **George E. Georghiou:** Conceptualization, Supervision, Writing - review & editing.

Declaration of competing interest

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

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Annex A

Table 9
Formulations, objectives and modelling constraints of references dealing with shared rooftop solar, community-owned solar and individual storage.

Ref.	Optimisation	Objective			Modelling and constraints				
		Economic	Environmental	Technical	Storage	Demand response	Area	Network	Sector coupling
[36]	–	✓	–	✓	✓	–	–	–	–
[50]	✓	✓	–	–	–	–	✓	–	✓
[51]	✓	✓	–	–	✓	–	✓	–	✓
[52]	✓	✓	–	✓	✓	–	–	–	–
[53]	✓	✓	–	–	✓	–	✓	–	✓
[60]	–	✓	–	–	✓	–	–	–	✓
[61]	✓	✓	–	–	✓	–	✓	✓	–
[75]	✓	✓	–	–	–	–	✓	–	–
[94]	✓	✓	–	–	–	–	✓	–	✓
[95]	✓	–	–	✓	–	–	✓	✓	–
[96]	✓	✓	–	–	✓	–	–	–	–
[97]	✓	✓	–	✓	✓	–	–	–	–
[98]	–	✓	–	–	–	–	✓	–	–
[99]	✓	–	–	✓	–	–	✓	–	–
[100]	–	–	–	✓	✓	✓	✓	–	✓

Table 10
Formulations, objectives and modelling constraints of references dealing with community-owned storage.

Ref.	Optimisation	Objective			Modelling and constraints				
		Economic	Environmental	Technical	Storage	Demand response	Area	Network	Sector coupling
[30]	✓	✓	–	–	✓	–	n.a.	–	✓
[31]	–	✓	–	✓	✓	–	–	✓	–
[32]	–	✓	–	✓	✓	–	✓	–	–
[34]	✓	✓	–	✓	✓	–	–	–	–

Table 11
Formulations, objectives and modelling constraints of references dealing with hybrid and multi-energy systems.

Ref.	Optimisation	Objective			Modelling and constraints				
		Economic	Environmental	Technical	Storage	Demand response	Area	Network	Sector coupling
[33]	–	✓	✓	–	✓	–	✓	–	✓
[35]	✓	✓	✓	–	✓	–	✓	–	✓
[37]	✓	✓	✓	–	✓	–	✓	–	✓
[38]	✓	✓	✓	–	✓	–	n.a.	✓	✓
[101]	✓	✓	✓	–	✓	–	✓	–	–
[102]	✓	✓	–	✓	✓	–	✓	✓	✓
[103]	✓	✓	–	–	✓	–	–	–	✓
[104]	–	✓	✓	✓	–	–	✓	–	✓
[105]	✓	✓	–	–	✓	–	✓	–	–
[106]	–	✓	✓	–	–	–	✓	–	✓
[107]	✓	–	–	✓	–	–	✓	–	✓
[108]	–	–	–	✓	✓	–	✓	✓	✓
[109]	✓	✓	–	–	✓	✓	–	–	✓
[110]	✓	✓	✓	–	✓	✓	✓	–	✓
[111]	✓	✓	–	–	✓	–	✓	–	✓
[112]	–	✓	✓	✓	✓	–	n.a.	✓	✓
[113]	✓	✓	✓	✓	✓	–	✓	–	✓
[114]	✓	✓	–	–	✓	–	✓	–	✓
[115]	–	✓	–	–	✓	✓	–	–	✓
[116]	✓	✓	–	–	✓	–	✓	✓	✓
[117]	✓	✓	✓	–	✓	–	✓	–	✓
[118]	✓	✓	–	✓	✓	–	✓	–	–
[119]	✓	✓	–	–	✓	–	✓	–	✓
[120]	–	✓	✓	✓	✓	–	–	–	✓

Table 12
Formulations, objectives and modelling constraints of references dealing with district heating and cooling.

Ref.	Optimisation	Objective			Modelling and constraints				
		Economic	Environmental	Technical	Storage	Demand response	Area	Network	Sector coupling
[18]	✓	✓	✓	–	✓	–	✓	✓	✓
[19]	✓	✓	✓	✓	✓	–	✓	–	–
[39]	✓	✓	–	✓	✓	–	✓	–	✓
[40]	–	✓	✓	✓	✓	–	✓	–	✓
[41]	✓	✓	–	–	✓	–	✓	–	✓
[42]	✓	✓	–	–	✓	–	✓	✓	–
[43]	✓	✓	✓	✓	✓	–	–	–	–
[44]	✓	✓	✓	✓	✓	–	–	✓	–
[45]	✓	✓	–	–	–	–	–	–	✓
[46]	✓	✓	–	–	✓	–	–	✓	–
[47]	–	✓	✓	–	✓	–	–	✓	–
[48]	✓	✓	✓	–	✓	–	✓	✓	✓

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