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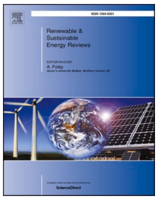

Feasibility and evolution studies on renewable energy communities in cities

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A B S T R A C T

Renewable energy communities could play a key role in the decarbonisation of the building stock, while providing important benefits to the members. This paper reviews the existing literature on this topic of growing scholarly interest. Three clusters have been identified, grouping the most common approaches to study feasibility analysis and the drivers that encourage individual participation. The paper also explores the role that different actors and forms of self-organisation might play in the development of these communities. The findings highlight a lack of homogeneity in the literature in conceptualising the benefits of renewable energy communities for different stakeholders. There is also evidence that little attention has been paid in the research to energy efficiency measures and the reduction of energy consumption. Financial costs and benefits are the main drivers, while environmental concerns and the desire to reduce dependence on energy-related uncertainties emerge as influential in community participation. Finally, a comparison of Italian case studies reveals a lack of comparability between studies due to discrepancies in the conceptualisation and calculation of indicators, such as the variation of self-sufficiency ratios ranging from 35.6 % to 83.8 % between reported and recalculated results. The insights gained from this study can help lay the ground for the establishment of a cross-sectorial approach to renewable energy community studies. A further important contribution of this work is to draw attention to the need for a common framework for assessing the performance of these communities. Finally, this study also usefully proposes clear calculation boundaries for the definition of indicators.

Nomenclature

Abbreviations	
GHG	greenhouse gas
EEM	energy efficiency measure
RES	renewable energy source
REC	Renewable energy community
CEC	Citizen energy community
RED II	Renewable energy directive
DSO	distribution system operator
KPI	key performance indicator
DES	distributed energy sources
PBP	payback period
EPHI	energy poverty help indicator
PtV	power to vehicle
PtP	power to power
PtG	power to gas
PtGtP	power to gas to power
PtH	power to heat
NPV	net present value
IRR	internal rate of return
LCoE	levelized cost of energy
MILP	mixed integers linear programming
CAPEX	capital expenditure
OPEX	operational expenditure
PV	photovoltaic
COP	coefficient of performance
EER	energy efficiency ratio
GIS	geographic information system
ABM	agent based model
VSC	virtual self-consumption
PSC	physical self-consumption
EEA	European economic area
Symbols	
SCR	self-consumption ratio
SSR	self-sufficiency ratio
$SC_{i,t}$	self-consumed energy for vector *i* [kWh_i/t]
$E_{wit,i,t}$	energy withdrawn from the grid for energy vector i. [kWh_i/t]
$E_{fed,i,t}$	energy fed into the grid for energy vector *i*. [kWh_i/t]
$f_{p,i}$	conversion factor to primary energy for vector *i* [kg_{CO2eq}/kWh_i]
$C_{i,t}$	energy consumption for energy vector i [kWh_i/t]

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(*continued*)

C_{inv}	initial investment cost for the establishment of the REC [€]
$CO_{2eq,emis,t}$	CO_2 emitted by the REC [kg_{CO2eq}/t]
$C_{en,t}$	community expenditure for the purchase of energy [€/t]
Subscripts	
el	electricity
gas	natural gas
tot	total
V	vehicle
i	i-th energy vector
t	time
REC	renewable energy community
resid	residential members
sav	savings
emis	emissions
s	proposed scenario
b	baseline scenario

1. Introduction

Urban areas account for approximately 75 % of global primary energy consumption and are responsible for a significant share of total greenhouse gas (GHG) emissions [1]. Given that the majority of the global population resides in urban areas [2], it is evident how cities can play a pivotal role in climate change mitigation. In recent decades, a considerable number of policy frameworks [3] have been implemented, strengthening carbon neutrality targets [4] for the improvement of urban environmental sustainability.

These efforts have also been supported by the recognition of the link between energy resources and economic fluctuations [5]. For example, energy prices in recent years have led to significant imbalances between countries, ultimately affecting national economies, in a context that is expected to worsen [6]. As a consequence, countries need to anticipate and counterbalance the potentially disruptive effects of a collapse of system-critical actors [7].

In Europe, the building sector alone is responsible for approximately 36 % of energy-related CO_2 emissions and 40 % of primary energy consumption [8]. Within this sector, the implementation of energy efficiency measures (EEM) in conjunction with generation of energy from renewable sources (RES) represents a significant potential for the reduction of operational carbon emissions [9]. This assertion is substantiated by initiatives such as REPowerEU action [10], while also underscoring the potential for sector coupling synergies [11].

At present, the transition towards the use of clean energy at the urban scale is progressing slowly [12], while inherent technological issues remain unresolved, including generation-consumption mismatch [13] and the non-programmability of RES [14]. In order to address the slow pace of this transition, citizen-led bottom-up initiatives [15] are gaining attention due to their capability to integrate citizens as active actors in the energy market [13,16,17], increase energy consumption awareness [18,19], and enhance individuals' "energy literacy" [20]. The aggregation of consumers in participatory schemes is not a novel concept. Expanding energy analysis to the neighbourhood scale [21] in order to exploit the potential of diverse building typologies and consumption curves [22,23] has been explored using a range of terms representing different carbon neutrality objectives and temporal discrepancies between energy production and generation [24,25].

Recent developments in European legislation have given rise to two novel forms of energy-related associative entities, namely Renewable energy communities (RECs) and Citizens energy communities (CECs). RECs are defined by the recast of the EU Renewable energy directive (RED II) [26], while CECs are introduced by the EU Internal electricity market directive [2,27]. Both entities can engage in different activities along the energy supply chain, such as production, consumption, storage, sharing among members, and selling. RECs and CECs emphasise the change in citizens' role, from passive consumers to active prosumers, and the need to consider factors beyond the mere financial motivations in their implementation [28,29]. While exhibiting similarities, RECs and CECs also differ in their formulation. CEC is intended as a more general concept [30], encompassing the possibility to exploit non-RES [31,32], without geographical restriction, whereas RECs are limited to the production of energy only from RES, and by a proximity criterion [33,34], and are thus considered as "Community of place and interest" [35]. These differences substantiate the hypothesis that the RECs may align more directly with the decarbonisation target of the urban building stock. For the purposes of the present investigation, the remainder of this work focuses specifically on RECs.

In accordance with RED II, EU Member States must establish an "enabling framework" with the aim of facilitating the formation of RECs and ensuring the inclusion of low-income and vulnerable consumers [36]. This framework is required to facilitate access to finance and information, as well as to promote collaboration with distribution operators (DSO) [26]. It has been asserted that the correspondence of RECs impacts with the outcomes and benefits envisaged by the EU directives is contingent on the attractiveness and coherence of the enabling framework [34]. Furthermore, consumers' willingness to participate has been stressed as fundamental in the deployment of RECs [37], as well as their social acceptance [18]. In this direction, the enabling framework should consider the motivations behind actors' decision to participate or not, and their potential incapability to do so.

In the broader context of community energy [12], numerous studies have highlighted the significance of both external (e.g. costs, policies, energy models) and internal factors (e.g. financial and attitudinal) in influencing citizen participation [38–40]. Consequently, a thorough examination of the motivations, and external influences that drive the adoption of RECs is paramount, in conjunction with technical design considerations [40,41]. However, there is a paucity of approaches to evaluate how motivations vary across consumers [42,43], as well as a lack of a comprehensive evaluation framework able to consider the different potential benefits brought by the implementation of a REC [30,44,45].

The main objective of the literature review is twofold: firstly, to evaluate how feasibility and constitution of RECs are evaluated from different academic viewpoints; and secondly, to evaluate their different focal points, with a view to providing possible insight for future research on the topic. Indeed, it is crucial to adopt a transdisciplinary approach to ensure the supporting role of RECs in the energy transition. Such an approach is necessary to avoid the risk of unbalanced deployment of the latter [46], and should be informed by a triple-bottom-line approach.

RECs have been considered aligned with several of the United Nations' Social development goals as outlined in the Agenda 2030 (affordable and clean energy, sustainable cities and communities, responsible consumption and production, climate action) [2], suggesting their capability to confer a range of benefits to various stakeholders. From an environmental perspective, RECs may encourage the acceptance of RES generation in urban areas [32,47], thereby contributing to the achievement of national decarbonisation targets [44], reducing GHG emissions, and implementing actions to mitigate the impact of cities [28,32]. Furthermore, RECs might increase energy security and independence [4,10,48,49], and enhance territorial resiliency [23]. They can provide flexibility services to the main grid [17,50,51], offsetting violations in voltage and capacity limits [52], and reduce its necessity for upgrades [53,54]. In urban environments, RECs could also promote energy efficiency at building level, decreasing energy consumption and emissions [28,37,55], enhancing energy self-sufficiency [15], and overcoming technical constrain at single building level [56,57]. The economic sphere, as well, is affected by the implementation of RECs. New jobs could be created [47,58,59], and market opportunities may emerge, offering prospects for profit-driven operators. Furthermore, members could benefit from energy bills savings and energy self-consumption.

In addition to the economic and environmental advantages, both the

European legislator and the scientific community place significant emphasis on the positive social impacts associated with the implementation of RECs. In conjunction with the promotion of citizen engagement and innovative forms of participation [2], RECs have been regarded as capable of combating energy poverty [2,32,33,60], with the ability to reduce consumption and facilitate affordable energy tariffs [23,61,62] for demographic groups that are typically excluded from renewable energy investments and face split incentives issues [34,63]. Moreover, it has been documented that the establishment of energy communities in socio-economically disadvantaged and mistrusted neighbourhood has been associated with an enhancement in the civic sense of residents [64], leading to a reduction in the stigma experienced by marginalised groups [65].

Notwithstanding the aforementioned benefits, there are several challenges that may emerge if the impacts of the implementation of RECs is not given full consideration. This calls for a need to guide their implementation both from a design [62] and a policy point of view [10]. For instance, the wide spread of distributed generation could bring issues to the stability of the energy system [13,17,24] with excessive stress on grid components determined by energy flux inversion due to generation-consumption mismatch [66]. Furthermore, there might be a misalignment of goals between RECs and other operators [44], determining potentially negative impacts of the community itself [61]. For instance, private members might target profits maximisation, the DSO might value the avoidance of grid update necessity, while local authorities might be interested in the social and environmental benefits generated by RES upscaling [49]. The presence of such potentially conflicting goals calls for a concertation of actions to avert adverse outcomes for specific actors, with the possibility to evaluate the introduction of policies and price signals that could direct a coordinated deployment of RES [67].

Finally, numerous barriers may be faced by citizens willing to participate in a REC, including space limitation for distributed generation [68], high investment cost, lack of access to finance [36,44], issues related to socio-economic factors [12,69] knowledge [30] and regulation [13]. These factors might result in an uneven distribution of RECs across cities and socio-economic groups [34]. This uneven distribution argument could be further substantiated by the fact that, in the process of designing a RECs, a variable that could be optimised is the selection of participants so as to achieve higher financial results [70]. The focus on maximizing profits in the implementation of RECs may result in a neglect of areas where greater social, economic, and environmental benefits could be achieved [32]. This could lead to a harmful polarization effect between classes residing in sustainable areas and disadvantaged classes living in more polluted areas [71]. In this sense, a comprehensive framework to evaluate REC projects is required, taking into account the variety of criteria (social, environmental, and economic) and stakeholders (DSO, prosumers, consumers, and public authorities) and particularly their trade-offs in the desirability of alternatives.

Several literature reviews have been published on the subject of RECs, focusing on a variety of areas including regulatory frameworks [28], mathematical modelling [44,72,73], business models [72,73], technologies and sector coupling [74], analysis of actors roles and structures, as well as barriers and benefits [44] and key performance indicators (KPIs) in the formation and operational phase of RECs [44,73].

This work is distinguished from previous studies by its objective to map how the feasibility of RECs is evaluated by different scientific approaches, from both a technical and behavioural perspective, in order to evaluate potential cross-contaminations among sectors. Furthermore, a meta-analysis of the Italian subset of case studies is performed to evaluate inconsistencies among the indicator used, and a homogenised set of KPIs is proposed. Finally, potential hindering and promoting factors in the constitution and governance of RECs are examined, those being usually neglected in the predominantly technical feasibility approaches.

The remaining of the work is organized as follows: section 2 presents the methodology; section 3 classifies the reviewed articles based on their approaches and main goals; section 4 analyses the nexus between energy generation and consumption reduction; section 5 presents insights on the governance dynamics of RECs; and section 6 compares the subset of Italian case studies and proposes a set of KPIs. Finally, section 7 draws conclusions.

2. Methodology

The research was conducted in accordance with the PRISMA methodology, encompassing a systematic search of the Scopus database. The primary keyword employed was “energy community”, accompanied by a series of geographical constraints keywords, including “urban”, “city”, “neighbourhood”, “district”, “block”, and “municipality”. A further limitation was imposed to include only journal papers in the English language, yielding a total of 349 documents. Fig. 1 presents the temporal distribution of the selected papers. The introduction of the European directives between 2018 and 2019 is evident in the number of academic products on the topic, especially in the European economic area countries. For this reason, only papers published after 2018 have been further analysed.

It is important to underline that the decision to prefer the term “energy community” over “Renewable energy community” is primarily due to the fact that a broad array of appellations has been employed in literature to define groups of individuals engaged in energy-oriented endeavours, not necessarily constrained to financial motivations [24,25,28]. Moreover, the utilization of the terminology introduced by the European Union would have likely constituted a Eurocentric limitation. Consequently, a number of studies that refer to configurations not precisely aligned with the definition of REC have been included in the analysis, for example those from the community energy field.

A second skim of documents has been conducted based on article title and abstract, including only contribution considering case studies, excluding those focusing on technical aspects of RECs operation (such as. blockchain technologies or energy exchange management with the grid), or those focusing on technical analysis of grid components. The resulting documents have been further analysed according to the goals set for this contribution. The flow diagram used for the selection of articles is presented in Fig. 2.

3. Ways to analyse RECs

With regard to the feasibility and potential establishment of RECs within an urban environment, three primary approaches have been identified, and they are described in this section. The proposed clusters do not refer to specific sub-fields or disciplines; instead, they are defined according to the similarities in the viewpoint used to analyse REC formation, as well as citizens’ attitudes towards them. The aforementioned clusters are defined in a loose manner as follows: (i) “Scenario comparison”, (ii) “Portfolio optimisation”, and (iii) “Behaviour analysis”. The first two clusters are characterised by the aim of defining the most suitable REC layout for specific areas, evaluating the availability of renewable sources, and examining alternative technologies and configurations. The first cluster is based on a discrete space of solutions (scenarios) and considers different KPIs to support decision-makers in selecting the preferred solution. The second cluster employs optimisation models operating on a continuous space of solutions to identify the optimal portfolio of technologies in accordance with pre-determined objectives. A degree of overlap can be identified between the two clusters in studies that compare different scenarios following initial optimisation (post-optimal comparison). In distinction to the previous two groups, the “Behaviour analysis” cluster seeks to identify individuals’ motivators and to model their propensity to participate in RECs. The analysis of these three clusters is focused on identifying the specificity of research goals, with the aim of understanding the potential for the cross-

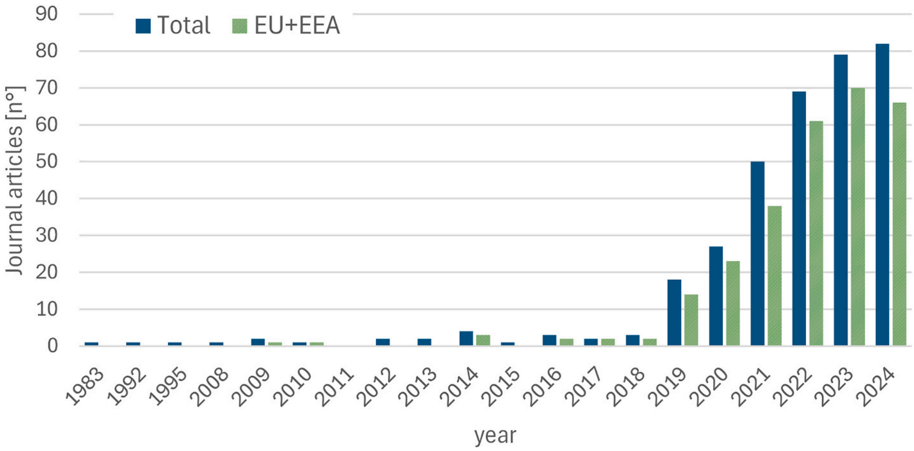

Fig. 1. Publication trend of the collected articles worldwide, and in the European + European economic area (EEA).

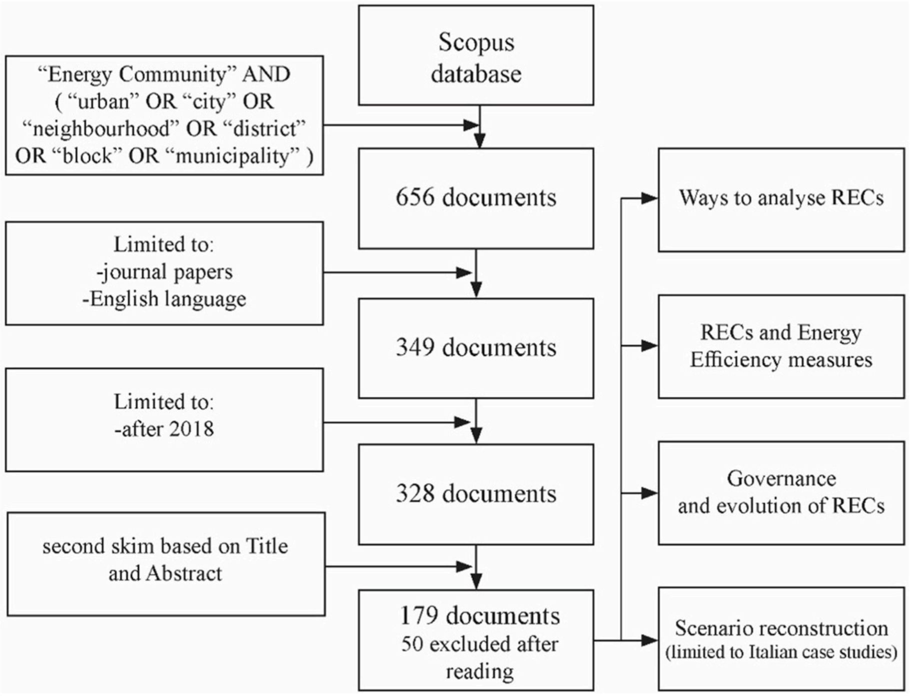

Fig. 2. Structure of the literature review.

sectorial approach to RECs analysis [75].

3.1. Scenario comparison

The first cluster groups studies that aim to compare different alternatives of intervention for the constitution of a REC. This approach is particularly targeted to support decision makers when potentially conflicting or incommensurable performance indicators are present [76,77]. The production in this cluster includes several works that have evaluated alternative technology combinations to address district/municipality energy demand [3,14,25,78], the introduction of energy efficiency measures [79–82], alternative system controlling strategies [14,83], as well as REC size and configuration options [13,36,82,84]. A growing body of research has focused on the benefit associated with synergies among end-users' aggregating consumption patterns [22,51], also leveraging on residual energy such as from industrial processes [85]. Another line of research focuses on the potential of alternative Power-to-X strategies [24,25,78,86] such as the integration of electric (PtP), thermal (PtH), vehicles (PtV), and hydrogen (PtG) storage strategies of locally produced energy surplus [24,78]. Finally, several works focus on the relations between distributed generation and the impact that it could have on the main grid.

Table 1 provides an overview of the indicators used in the selected studies to evaluate the competing alternatives, and shows the combinations of KPIs in the four typically evaluated dimensions (i.e. economy, energy, environment, and social).

Among the evaluated papers, the economic dimension is the most analysed one, with an array of indicators employed, including payback period (PBP), net present value (NPV), internal rate of return (IRR), levelized cost of energy (LCoE), benefit/cost ratio, and annual cost. In addition, the energy dimension, typically evaluated through the self-sufficiency ratio (SSR) and the self-consumption ratio (SCR), is considered in more than half of the cases, in accordance with the necessity for RECs to deliver benefits that extend beyond financial ones. With respect to the multi-objective nature of RECs, numerous studies utilise a combination of indicators, with 15 documents evaluating REC feasibility

Table 1

Overview of indicators used by the papers in the “Scenario building” cluster.

Source	ECONOMY						ENERGY								ENV.		SOCIAL		
	NPV	PBP	IRR	Investment cost	Cost & benefits	LCoE	Technical complexity	SSR	SCR	Energy generation	Grid interaction	Energy consumption	Seasonal COP	Seasonal EER	CO_2 emissions	Embodied carbon	“10 %” indicator	Comfort level	EPHI
[3]	X	X																	
[9]	X	X	X		X			X	X						X				
[13]	X							X			X								
[14]	X				X			X	X			X			X				
[22]	X		X		X			X	X						X				
[24]					X				X										
[25]	X	X						X	X						X				
[33],[a]																			
[36]	X				X			X	X						X				
[47]								X	X		X								
[49]	X	X		X											X				
[50],[a]																			
[51]								X	X	X		X							
[57]	X	X	X					X	X						X				
[60]		X						X	X			X			X		X		
[62]	X	X	X												X				
[65]		X										X							
[78]	X	X			X	X		X				X			X				
[79]	X	X						X				X			X	X			
[80]	X		X						X						X				
[81]	X							X	X						X				
[82]					X			X	X						X				
[83]								X	X			X							
[87]							X			X								X	
[84]		X			X			X							X				
[86]					X	X		X	X						X				
[88]	X	X	X		X										X				
[89]								X	X			X	X	X					
[90]	X	X			X														
[91]									X			X			X				
[92],[a]																			
[93],[a]	X							X	X						X				X

[a] case studies for which a first optimization was performed (post-optimal comparison).

from environmental, economic and energy perspectives. As Gjorgievski et al. [44] previously observed, the social dimension is rarely addressed in REC analyses, with only a few studies attempting to factor it into the evaluation framework. For instance, Ceglia et al. [60] analysed the effect of the establishment of a REC on the "10 %" indicator usually used to quantify energy poverty. Cutore et al. [33] propose the energy poverty help indicator (EPHI), to assess the number of families in energy poverty conditions benefitting from the distribution of revenues from energy surplus. In this article, the dependency of energy poverty alleviation performance on members' goals is used to raise the argument regarding potentially conflicting outcomes of the proposed REC.

These initial results underscore the multidimensional and multi-actor nature of RECs, marked by the existence of incomparable KPIs and a multitude of perspectives in the evaluation of their impacts. Decision-making problems of this nature are specifically addressed by multi-criteria analysis methods, intended to rank alternatives and to prioritize criteria. Among the analysed studies, Efthymiou et al. [62] combined multi-criteria and SWOT analysis to support the selection of the layout of a municipality-led REC, together with the most appropriate business model to be implemented. Sibilla and Abanda [87] utilised PROMETHEE method to prioritize retrofit alternatives for a community of school buildings, against qualitative and quantitative indicators. Torabi et al. [37] assess retrofit scenarios of an educational complex against environmental, economic, technical, and social criteria, being the latter the visual quality after intervention.

Three principal limitations can be identified regarding the set of KPIs used in this first cluster. Firstly, the selection of KPIs varies depending on the focus of each study (municipality, DSO, or inhabitants' perspective). Secondly, the conceptualisation of indicators is problematic. For instance, the social impact represented by energy poverty alleviation is related to the internal redistribution of revenues or incentives granted, thus only representing a different definition of an economic aspect. Finally, certain indicators pose problems in their calculation, as they are expressed in a qualitative manner [33,87], or in a scenario-dependent way. For instance, the calculation of SSR is sensitive to energy vector and final uses considered (e.g. accounting only for electric consumption or including also thermal loads in case of the introduction of heat pumps).

3.2. *Portfolio optimisation*

The second approach involves the analysis of continuous spaces of solutions to select the optimal portfolio of technologies by minimising or maximizing target performance. A range of optimisation techniques are available, with the most widely used being Mixed integer linear programming (MILP) [53]. An optimisation process comprises three main components: (i) variables, (ii) constraints, and (iii) objective functions [94]. The first component, "variables", refers to the alternative technologies to be selected, taking a binary (absence/presence of a specific technology), or continuous form (sizing of a technology) [92]. Their specification allows for the optimisation of the displacement of DES in the most suitable locations [95], the evaluation of hybrid energy systems [50,96], and the enhancement of the complementarity of energy production and storage systems [34]. The second component, "constrains", represents the boundaries of the space of solutions, which can be categorised as either internal (e.g., equipment sizes, availability of space for installation) or external to the portfolio (e.g., limitation to thresholds violations such as transformer overload, or comfort degradation [53,66]). Finally, the objective function represents the performance to be either minimised or maximised.

The selection of the optimisation function is indicative of the objectives and perspective of the decision-maker, as evidenced by the predominance of studies that target the minimisation or maximisation of economic costs and benefits for REC members. Such studies generally account for investment (CAPEX) and operational (OPEX) costs, or utilise economic indicators such as NPV or PBP. For example, Monsberger et al. [97] utilise MILP to investigate the optimal REC layout, varying the objective functions according to the business model selected by a simulated initial investor. Other studies assume the DSO's viewpoint. For instances, Simoiu et al. [56] set an objective function that minimises the net-energy exchanged with the grid, while Delarestaghi et al. [54] optimise grid reinforcement intervention and consumers' investments by minimising investment and operational costs for both utility and consumers. Liu et al. [98] introduce a penalty cost to account for the extra burden to the grid caused by off/on-peak energy import/export.

In several cases, the formulation of the optimisation problem considers also the environmental and energy dimensions while selecting the technology portfolio, with this attempt being performed in three possible ways [99]. The first approach (i) involves converting GHG emissions into economic terms and minimising the total cost [50] in the target function formulation. The second approach, (ii) referred to as epsilon constraint method, allows the required performance to be specified as a further constraint. This approach has been used to guarantee a minimum of primary energy savings [100] and carbon emission reduction [99], as well as to constrain SSR and SCR while minimising costs [23]. Other works consider the impacts of RECs on the grid by applying a constraint to peak power exchange [101], and to energy surplus fed into the grid [66]. Finally, a third approach (iii) involves the introduction of an additional objective function, transforming the optimisation problem into a multi-objective one [45], often presented as n-dimensional Pareto fronts [59,96,102].

The Pareto front representation of solutions enables decision-makers to specify their trade-offs concerning different performance levels, allowing for weak sustainability compensatory mechanisms among criteria [102,103]. In such a way, different criteria can be perceived as not equally important by the decision-maker, who can assign them different weights in the process of selecting among solutions. This latter approach poses several questions related to subjectivity and the sensitivity of outcomes to weights elicitation [104]. Another approach is represented by the minimum distance to utopia. This method identifies a hypothetical alternative that optimises all evaluation criteria simultaneously (corresponding to the origin of the axis in a Cartesian representation of solutions) and selects the closest attainable solution in Euclidean terms from that utopic unreachable point [103]. Among these studies, Liu et al. [98] produce a three-dimensional Pareto front considering SSR, SCR, and the time-of-use grid penalty cost (thus considering grid relief potential provided by the REC). Ascione et al. [105] adopt this approach to discuss three suboptimal points in the solution space representing the preferences of private individuals (economic driven), municipality preferences (environmental driven), and the minimum distance from utopia as a mediated one.

In general, the mathematical definition of the optimisation problem requires the prioritization of one perspective over others by specifying in advance the target performance to be optimised. Some studies overcome this limitation by first optimizing the technology portfolio and then comparing the obtained scenarios against sets of indicators (post optimal selection) [33,50,92,93].

Table 2 presents an overview of the parameters specified in the optimisation functions utilised in the analysed documents, as well as the combinatory strategy employed to address the multiple dimensions of the problem. It is noteworthy that economic indicators predominate, and there is a relatively frequent attempt to introduce environmental and energy dimensions into the optimisation functions. Only a few studies evaluate these two dimensions independently, and only one introduces prosumers' comfort by monetising disutility due to the application of demand-response strategies.

A potential limitation of this cluster could be seen in the arbitrary definition of the geographical boundaries of the case studies examined. The optimisation of portfolios in a certain area might result in a suboptimal solution if the investigation area is expanded, especially in cases where a regulatory framework imposes limits on the geographical configuration of RECs (e.g., the Italian context). Interesting approaches

Table 2

Overview of the papers in the "Portfolio optimisation" cluster. Xm represents monetised variables, while Xϵ the ϵ-constrained variables.

	CAPEX	OPEX	peak use costs	SCR	SSR	energy balance	grid impacts	environmental impact	disutility cost	target min/max	Combinatory strategy	Source
Single objective optimisation	X	X								max (NPV)	–	[4]
		X	X							min		[10]
		X						Xm		min	CO$_2$ monetisation	[18]
				X						max	–	[18]
	X	X								min	–	[53]
	X	X	X						Xm	min	Users' disutility monetisation	[54]
							X			min		[56]
	X	X	X							min		[85]
	X	X								min	–	[94]
	X	X								max (NPV)	–	[95]
	X	X								min	–	[106]
	X	X								min		[107]
	X	X	X				Xm	Xm		min	CO$_2$ monetisation, slack penalties	[108]
ϵ-constraint method	X	X		Xϵ	Xϵ					min	ϵ-constraint (SCR, SSR)	[23]
	X	X					Xϵ			min	ϵ-constraint (positive net load)	[66]
	X, Xϵ	X, Xϵ								min	ϵ-constraint (alternatively CAPEX and OPEX)	[67]
	X	X, Xϵ								max (gains)	ϵ-constraint (residents' energy cost)	[97]
	X, Xϵ	X					Xϵ	Xϵ		min	ϵ-constraint (maximum energy withdraw, CO$_2$, breakable investment constraint)	[99]
	X	X				Xϵ				min	ϵ-constraint (primary energy consumption)	[100]
	X	X	X				Xϵ			min	ϵ-constraint (peak power exchange)	[101]
Post-optimal comparison	X	X								max (NPV)	Post-optimal evaluation (SCR, SSR, CO$_2$ emissions, EPHI)	[33]
	X	X						Xm		min	CO$_2$ monetisation, Post-optimal evaluation (energy self-consumed, purchased, and used; grid capacity, storage capacity, CO$_2$ emissions)	[50]
	X	X								min	Post-optimal evaluation (LCoE, SSR)	[92]
	X	X								max (NPV)	Post-optimal evaluation (SCR, SSR, CO$_2$ emissions, EPHI)	[93]
Multi objective optimisation	X	X					X			min-max	Multi-objective cost-grid sustainability index	[45]
	X	X						X		min-min	Multi-objective NPC-ReCiPe indicator, post-optimal evaluation (renewable energy fraction, Energy Performance Indicators, economic and environmental PBP, employment opportunities)	[59]
	X	X				X				min-min	Multi-objective Life-cycle costs-imported electricity	[96]
			X	X	X					min-max-max	Multi-objective grid penalty-SCR-SSR (Post-optimal evaluation NPV, CO$_2$ emissions)	[98]
	X	X						X, Xm Xϵ		min-min	Multi-objective cost-emissions (further ϵ-constraint on CO$_2$, and introduction of carbon taxes)	[102]
	X	X						X		min-min	Multi-objective global cost-CO$_2$ emissions	[105]

to address this potential issue are those that attempt to evaluate the matching between energy demand and consumption at the city scale using GIS tools [109,110]. Furthermore, it is important to consider the evolution of RECs over time, as the optimised solution might limit the desirability of including new members after the first implementation of the community [4]. Additionally, the evolution of consumption pattern (i.e. due to electrification of consumption and energy demand reduction thanks to the introduction of energy efficiency measures) may modify the boundary conditions on which the optimisation is based.

3.3. Behaviour analysis

The final cluster of studies encompasses papers that concentrate on the motivations behind inhabitants' participation in a REC, in addition to the potential evolution of REC formation. With regard to the evaluation of drivers and motivation in REC participation, real-word case studies have been utilised as sources of information. By conducting interviews with members of both existing and emerging energy communities, several authors have noted a preference for independence from the distribution grid [111], with a tendency towards autarkic discourses, even when the proposed solution was not economically or environmentally advantageous [112]. This regain of control has been posited as a means to tentatively mitigate various forms of uncertainties associated with geopolitical conflicts, escalating energy prices, and environmental challenges [113,114]. The environmental factor has been identified too as a motivator for engagement in both existing communities [12] and experimental simulations [115], with the presence of grants, subsidies, and other forms of incentives being recognised as a prerequisite [12]. The interest in the environmental impacts of RECs has also been confirmed by the application of discrete choice experiment methods, with the social aspect also deemed an important driver [116], even if sometimes considered secondary to the environmental one [117], especially in cases where context factors (e.g., legal barriers, lack of incentives) fail to foster RECs formation [118]. The application of discrete choice experiment has yelled insights into the characteristics and configurations of RECs, which have the potential to either impede or encourage individual participation. Among the characteristics that have been observed and linked to individuals' socio-demographic and attitudinal attributes are ownership regimes of the energy generation systems [119], the involvement of municipalities and firms, governance characteristics such as voting rules [116], investment options, risks and losses, and other co-benefits [117].

The nexus between individual attitudes and characteristics, and the diffusion of RECs is the focal point of a body of research that utilises agent-based models (ABM) to simulate individuals' decisions regarding renewable generation projects. ABMs have commonly been employed to evaluate the evolution of a system under specific conditions, capturing the dynamic interaction among individuals [40,120], factoring in the time variable in the evaluation of the system [121]. In ABMs, agents are modelled as autonomous entities capable of deciding whether or not to act, considering various characteristics including attitudinal factors, socio-economic parameters, motivations, and interactions with other agents [1,40]. In the initialisation stage of an ABM (time 0), each agent is assigned an internal state represented by variables describing the propensity to act or not. At each time step, an agent determines whether to act or not, based on a set of rules defined by the modeller [40]. These rules delineate the manner in which the internal state of the agents are modified over time and through interaction with other agents [1]. The way in which these behavioural rules are specified by the modeller constitutes a pivotal step in the implementation of ABM, necessitating the collection of extensive data to ensure their accurate determination [120].

Of the studies analysed, Mittal et al. [40] modelled the willingness of agents to participate in a "community solar" project, defining a set of NPV-based behavioural rules moderated by individuals' attitudes towards systems ownership and environmental concerns. Schiera et al. [1] integrated Theory of planned behaviour, Relative agreement and Small-world network to simulate the diffusion of distributed generation systems. Fouladvand et al. [122] simulated the behaviour of inhabitants confronted with the possibility to join a forming REC or an existing one, or the conditions under which the individual would decide to drop-off from a community after being a member. Building on Social value orientation, Fouladvand et al. [121] modelled the motivations and concerns of four person types (i.e. altruistic, cooperative, individualistic, competitive) deciding to join a REC. In this model, the primary motivations of the agents in joining the REC were energy independence, a sense of community, environmental concern and economic benefits.

ABMs present limitations in the way they describe the world [121]. Indeed, there is a certain degree of discretion in determining agents' behaviour according to predefined sets of mathematical rules and thresholds [1]. Studies employing this method may utilise the results and methodological approach of research based on real case ex-post evaluation, as well as those employing choice experiments, in order to expand the analysis of consumers' motivations and trade-offs toward the adoption of renewable energy solutions [40,121], to quantify and test the decision models specified through the decision rules as well as the assignment of inhabitants to different clusters of initial attitudinal states [121,122].

The studies belonging to this last cluster could be useful in evaluating the possible spread of RECs as well as their contribution to the energy transition [118]. However, further analysis of people's motivations and values (also in quantitative terms) is necessary to support the role of policymakers in taking actions fostering citizens' participation [1].

4. RECs and energy efficiency measures

The positive implications of a large penetration of RECs are manifold, with the alleviation of energy poverty frequently highlighted among the social benefits. Energy poverty affects around 8 % of the European population [60], with a link, especially among vulnerable groups, to poor conditions and low energy efficiency of buildings [37,87]. Such interconnection between efficiency and distributed generation has been already stressed at European level [123]. It has been noted that RECs mainly focus on production from RES and not on energy consumption reduction [124]. While some research addresses this by integrating RECs in advanced district heating networks to avoid major refurbishments [125], few articles in the revised literature on RECs evaluate simultaneously energy production and consumption reduction. This still represents a limitation in the state of the art on the topic [105]. Amongst this limited number of articles, Mutani & Usta [81] considered the application of a REC to two condominiums in Italy, evaluating it with and without retrofit interventions. The study found that the implementation of a REC led to a reduction in energy consumption by 28 % compared to the existing situation. Additionally, it reported a 26 % increase in SSR and a noteworthy 11 % increase in SCR. Sougkakis et al. [80] evaluated the financial benefits of performing a renovation of an existing neighbourhood in Greece, acting individually or as a community of inhabitants. Mutani et al. [82] evaluated the constitution of a REC in a small Italian town, pooling together several types of actors, among which the municipality. They evaluated the different performance of various scenarios, considering the possibility to reduce the energy consumption of public lighting, reporting, as predictable, an increase in SSR for more energy efficient interventions. Ascione et al. [105] analysed four mainly residential buildings in Italy, integrating the installation of roof-mounted PV panels with various EEMs, while also taking into account the impact of incentive schemes. Through an examination of the results on a multi-objective Pareto front, the authors identified the variation in the suitability of alternatives due to public grants. They concluded that such incentive schemes should prioritize the promotion of PV adoption over EEMs. It could be argued that this conclusion might be specific to the case under consideration and that incentivising distributed energy generation without simultaneously promoting the curtailment of energy consumption could reduce the environmental benefits associated with RECs [82], as well as cause potential problems to the main grid due to a generation/consumption mismatch [81,101].

There is a broad consensus that the combination of RECs and EEMs adoption at the building scale can have significant economic and environmental benefits. However, it should be noted that, to the best of the authors' knowledge, all the articles considering energy efficiency in their analysis belong to the comparison and optimisation clusters, as previously identified. This imply that no real-world case studies have been found in the current literature, representing the combination of EEMs and distributed generation still a niche topic.

It could be argued that neglecting retrofit constitutes a sub-optimal approach to the debate on RECs contribution to the decarbonisation of the building sector, and also represent a misalignment between proposed solutions and the range of benefits (and potential risks) that a REC is ought to bring. In addition, given the progressive electrification of thermal uses [113], retrofit interventions are likely to play a pivotal role in ensuring a higher level of self-sufficiency, while limiting negative effects on the electricity grid (by reducing the generation/consumption mismatch). Finally, behavioural and demand management strategies regarding the willingness to modify individuals' consumption patterns [108,115] could represent a significant research avenue for optimizing the use of locally generated energy.

5. Governance and evolution of RECs

The analysis of numerous real-world cases of energy communities has revealed a variety of contextual factors capable of promoting or hindering the diffusion of RES [12], as well as conditions that might determine their successful implementation and scalability [126,127], also leading to different forms of association [127]. In this regard, the role of institutional actors, such as municipalities, has been recognised as pivotal in the establishment and evolution of RECs, as well as in their governance [128]. In particular, it has been observed that individuals' attitude toward the establishment of energy communities are positively influenced by the participation of institutional actors in the process [126,129], or by the institutionalisation of the community itself [127]. Despite being constrained by a lack of control over local energy infrastructures and fiscal austerity [128], local authorities can play a pivotal role in fostering community acceptance [113]. Municipality-led RECs are usually favoured over enterprise-led ones by individuals [114,116]. Furthermore, the necessity to avoid uncoordinated development [67,101,130] could be mitigated by the integration of municipalities in the formation and operation of a REC, with some studies proposing the inclusion of RECs in municipal planning, further prioritising areas characterised by high levels of energy poverty [32]. However, the role of municipalities in the governance of a REC, and especially the interaction between them and the local population, has been interpreted in conflicting ways in different studies analysing real-world examples. For instance, the supportive role of municipalities in the inclusion of residents in an active manner under all the aspects of REC operation has been highlighted [75,111]. Conversely, both the high investment costs and the level of professionalisation needed to manage and upscale such projects could require a deeper involvement of the central authority as well as specialised actors [113,128], resulting in a decrease in the local dimension and sense of community ownership [75,113], ultimately relegating residents to passive roles [128]. Nevertheless, the inclusion of local authorities within RECs has the potential to yield notable social benefits, such as facilitating the deployment of generation technologies (i.e. on public buildings) in disadvantaged areas [131], and serving as a guarantor in the allocation of profits [113].

The issue of profit redistribution is intrinsically linked to that of voting model within the community itself. Indeed, it has been posited that actors should be enabled to self-determine the internal organization of the community [126]. However, specific arrangements may have counterproductive effects, such as discouraging small investors when a capital-based voting rule is introduced [14]. This poses a further balancing dilemma between the involvement of the local community and the necessary access to financial capital.

Finally, real-word RECs have been regarded as dynamic structures, in which the original scope and activities carried out evolve over time [113,126]. This emphasises again the importance of a coordinated development at different planning levels, as well as the proper integration of institutional and local actors and stakeholders, balancing the voting model between financial and participatory instances.

6. Scenarios reconstruction

The analysis of the academic literature on REC feasibility has revealed a broad spectrum of indicators employed, along with inconsistencies in their conceptualisation and calculation. In this section, a meta-analysis is conducted, encompassing case studies within the Italian context. The objective of the analysis is to compare the performance achieved in these case studies, using a harmonised set of KPIs capable of providing a common description of such performance.

Fig. 3 provides a schematic representation of the boundaries and energy fluxes entering and exiting a REC. In light of the prevailing academic literature, three boundaries are delineated: one considering solely electrical uses, one encompassing both electrical and thermal uses, and a final one expanding the scope of analysis to include mobility uses.

In terms of descriptors, the performance of RECs could be evaluated by a limited set of indicators that outline the community feasibility and sustainability from a variety of viewpoints. These KPIs are summarised in Table 3.

In particular, the environmental sustainability of RECs could be described by its CO_2 equivalent emissions ($CO_{2eq,emis}$). Its interaction with the grid (a relevant aspect for the DSO) could be described by taking into consideration the energy taken from ($E_{wit,i,t}$), and fed into ($E_{fed,i,t}$), the national grid at each time *t*, for each energy vector *i* (i.e., controlling for its impacts on grid components [130]). The self-consumption ratio (SCR_i) is another significant indicator in the description of the interaction between the community and the grid, given the risk posed by excessive injection of locally produced energy on system stability [86]. The decision to utilise energy fed and not generated is substantiated by the need to consider potential transformations of energy from one vector to another, particularly in scenarios where Power-to-X strategies are implemented. The economic sustainability of the initiative is expressed by the initial investment cost (C_{inv}) and the expenses sustained by the community for energy purchase ($C_{en,t}$). Depending on the internal redistribution of financial benefits among members, the cost for energy purchase can also be interpreted as a social indicator when pursuing the goal of aiding disadvantaged segments of the population. It should be stressed here that this set of KPIs is among the most frequently used in the current production on RECs. Potential enhancements of the analysis could include the extension of the environmental scope, for example by incorporating life-cycle assessment approaches, or the addition of end-uses such as mobility ones (i.e., SSR_{tot+V}).

Finally, SSR is employed to assess the impact that the REC could have on the decentralisation of the energy system and the independence that the configuration could achieve from uncertainties such as price fluctuation and energy supply risks. A key limitation of the current production on REC (especially in the Italian case studies analysed) is the incomparability of the SSR indicator, defined as self-consumed over consumed energy. The boundaries within which this indicator is calculated are subject to variations depending on the energy produced and consumed for different energy vectors in the REC. To illustrate, in case studies where the electric vector covers only uses such as lighting and appliances, SSR considers only the share of consumption for those services [23], thus achieving high values of performance. Conversely, when

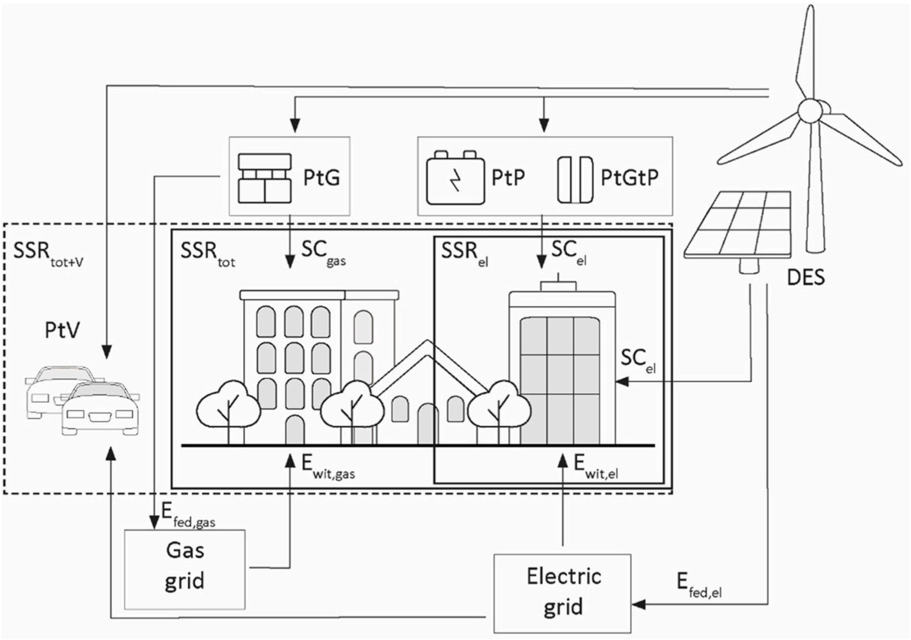

Fig. 3. Boundaries and energy fluxes considered in the meta-analysis.

Table 3
KPIs used to describe the RECs case studies.

$E_{wit,i,t}$	energy withdrawn from the grid for each energy vector *i* at time *t* (kWh_i/t)
$E_{fed,i,t}$	energy fed into the grid for each energy vector *i* at time *t* (kWh_i/t)
SSR_{tot}	self-sufficiency ratio (%)
SCR_i	self-consumption ratio for each energy vector *i* (%)
C_{inv}	initial investment cost for the establishment of the REC (€)
$CO_{2eq,emis,t}$	CO_2 equivalent emitted by the REC at time *t* (kg_{CO2eq}/t)
$C_{en,t}$	community expenditure for energy purchase at time *t* (€/t)

the electric vector also covers thermal uses [83], SSR takes a more comprehensive nature, achieving lower values. Furthermore, in scenarios proposing a transition from fossil fuel generators to electric ones, the augmentation of the electric uses determines an incommensurability between SSR among the compared alternatives [9]. Finally, a further source of discrepancy has been identified in the consideration of alternative storage systems, such as those employed in PtV strategies, or the conversion of electricity produced locally into other energy sources. This is exemplified by the production of hydrogen, which could be sold, blended into the national grid (PtG), or converted back to electricity (PtGtP).

In order to mitigate the aforementioned issues, this analysis has constrained the scope of the proposed total self-sufficiency ratio (SSR_{tot}), limiting its application to building-level uses such as heating, lighting, and appliances (thus excluding PtV strategies). The cooling service is seldom included in the analysed studies, as well as the domestic hot water one. While this might constitute a limitation, it could be argued that the considered uses are the most impacting ones in the existing Italian building stock. SSR_{tot} quantifies the energy used across the various vectors employed by a REC, according to equation (1):

$$SSR_{tot} = \frac{\sum SC_{i,t} * f_{p,i}}{\sum C_{i,t} * f_{p,i}} \tag{1}$$

where $SC_{i,t}$ is the self-consumed energy for vector *i* at time *t*, and $f_{p,i}$ is the conversion factor to primary energy for vector *i*. Self-consumption ($SC_{i,t}$) is calculated as in equation (2) in order to avoid double-counting of energy conversion in the REC (i.e., PtG or PtGtP):

$$SC_{i,t} = C_{i,t} - E_{wit,i,t} \tag{2}$$

where C_i is the energy consumption for energy vector *i* at time *t*, and $E_{wit,i,t}$ is the energy that the REC is not able to produce in its premises. It is necessary to highlight that in this meta-analysis $SC_{i,t}$ does not directly account for the energy exchange between grid and REC as it would be in a virtual self-consumption (VSC) configuration [33]. In case studies considering electricity to hydrogen conversion, the blending ratio within the national grid has been limited to 10 % [24]. Consequently, natural gas self-consumption ($SC_{gas,t}$) is calculated according to equation (3):

$$SC_{gas,t} = C_{gas,t} * 0.1 \tag{3}$$

As mentioned above, in order to calculate SSR_{tot}, it is necessary to take into account all the energy consumed at the building level. This is not only to determine the full impact of RECs, but also to simultaneously consider the decarbonisation of uses and the prior reduction of consumption, a strategy that, as highlighted, is rarely accounted in the current literature on RECs.

Several assumptions were made in order to reconstruct the scenarios and obtain comparable information from the meta-analysis. Firstly, the focus of this analysis is on the residential sector and the potential inclusion of occupants, so the normalisation of the indicators was carried out considering the dwelling as the basic unit (with some possible inconsistencies related to the different apartment dimensions (m^2), which were mitigated by averaging different sizes on a larger scales). In case of additional non-residential members, each KPI has been referred to the residential members (excluding SSR_{tot} and SCR_{tot}, which were kept equal to those reported for the total REC), based on the energy consumption according to equation (4):

$$KPI_{x,resid} = KPI_{x,REC} * \frac{C_{resid}}{C_{REC}} \tag{4}$$

where $KPI_{x,REC}$ is the performance reported in the case study, $\frac{C_{resid}}{C_{REC}}$ is the ratio of energy consumed by the residential uses to the total energy consumed by the REC, and $KPI_{x,\ resid}$ is the KPI limited to the residential members.

A second assumption is the inclusion of space heating use. Several studies do not take space heating into account, focusing mainly on PV-generated electricity. To overcome this limitation, typical space heating consumptions for different geographical locations have been derived from Canova et al. [9], and have been added to the energy consumption reported by those case studies neglecting their calculation.

Figs. 4–6 plot the recalculated performance against the investment cost (C_{inv}) from a residential perspective, assuming a physical self-consumption (PSC) configuration. SCR_i and $E_{fed,i}$ are excluded from the plots as their maximisation or minimisation may constitute a conflicting objective for different actors. In order to better compare these scenarios, C_{en}, and $CO_{2eq,emis}$ are given in terms of savings, according to equations (5) and (6):

$$CO_{2eq,sav} = CO_{2eq,emis,b} - CO_{2eq,emis,s} \tag{5}$$

$$C_{en,sav} = C_{en,b} - C_{en,s} \tag{6}$$

where the subscript *sav* refers to savings, *b* and *s* refer to the baseline and specific scenarios in each study, respectively. It should be noted that $CO_{2eq,sav}$, $C_{en,sav}$, and SSR_{tot} are presented on an annual basis.

As expected, all three figures show a direct correlation between investment costs and the three other indicators. Most studies report relatively low investment costs and low benefits in terms of energy savings and avoided CO_{2eq} emissions. These studies mostly focus on the electricity produced by the installed PV panels and express SSR in terms of the electricity vector only, thus achieving low levels of SSR_{tot}. All the best performing scenarios are those that introduce a heat pump ([11,24,83,132]) and consider different Power-to-X strategies. This is particularly evident in Canova et al. [9], where all the scenarios where heat pumps are introduced outperform those where only PV panels are installed, with an increase in SSR_{tot} between 7 % and 8 %. The same trend can be seen in Franzoi et al. [83], where the high performing scenarios also result in relatively low investment costs due to the presence of heat pumps in the status quo. Finally, the best performing scenarios in terms of CO_{2eq} and energy savings are by far those studied by Aruta et al. [132]. Here the strategy has been to set the investment costs similar to those for a deep renovation of the envelope. The best performing (from the environmental perspective) REC among all the studies belongs to this work, where the authors introduced a hybrid configuration with RES and EEMs (window replacement). It is worth noting that this solution refers to a rather moderate climate (a typical residential building in the same region consumes 89.04 kWh/m^{2}y [6], while the same building in different Italian regions presents energy consumption ranging from 59.2 kWh/m^{2}y to 238.8 kWh/m^{2}y [9]), which implies a potential different feasibility of other EEMs in colder zones.

Fig. 4 has been generated considering a physical self-consumption (PSC) configuration (except for Aruta et al. [132], where it was not possible to extrapolate the energy self-consumption). Although the authors recognise that this is a simplification and an overestimation given the current Italian legislation, which takes into account the use of the public grid as a buffer in determining energy tariffs and incentives, it is nevertheless useful to limit the assumptions for comparison purposes. A further analysis to mitigate this problem was carried out by considering 100 % of the energy self-consumed by the REC in a virtual self-consumption configuration, as shown in Fig. 7. The figure shows how the reduction in benefits associated with self-consumption affects the results, making the introduction of EEMs even more attractive and effective.

Several studies did not report SSR, but it has been calculated here on the basis of self-consumption and production data provided. For those that calculated SSR in their analyses, it is worth noting the difference in results when considering total energy consumption (recalculated according to equation (1)) instead of just electricity consumption (as presented in the analysed documents), with values 35.6 %–83.8 % lower than those originally reported. Fig. 8 shows this difference.

7. Conclusions

Renewable energy communities (RECs) could have a major impact on the energy transition in the built environment, mitigating its negative impact on GHG emissions in the urban context and thus representing a potential driver for urban renewal. According to RED II, RECs could bring several benefits to people and society, which are not only limited to the financial sphere, but also have a positive impact on the environmental and social dimensions. This literature review evaluated the common approaches used to analyse RECs in the feasibility phase as well as from the perspective of individual willingness to act, allowing for cross-sectional readings. Firstly, the study highlighted that the recognised lack of a comprehensive evaluation framework to assess RECs is also complicated by the inhomogeneity of the KPIs used (such as the economic or social aspect of energy cost reduction), and by the definition of the boundary set for their calculation (particularly for SSR_{el} and SSR_{tot} assessment). This inconsistency between boundaries can be related to the bias towards the productivity aspect of RECs, with less attention paid to consumption reduction. This is reflected in the tendency to rarely consider efficiency measures together with distributed generation solutions, thus limiting the potential (and neglecting risks) of RECs in supporting energy transition and reducing energy poverty. It is interesting to note that the studies that include energy efficiency measures in their scope of investigation belong to the feasibility analysis clusters, meaning that the introduction of energy efficiency measures in real-world case studies is a niche topic that is rarely explored.

In addition, this work analysed the literature findings on the governance and internal organisation of RECs, as well as their evolution over

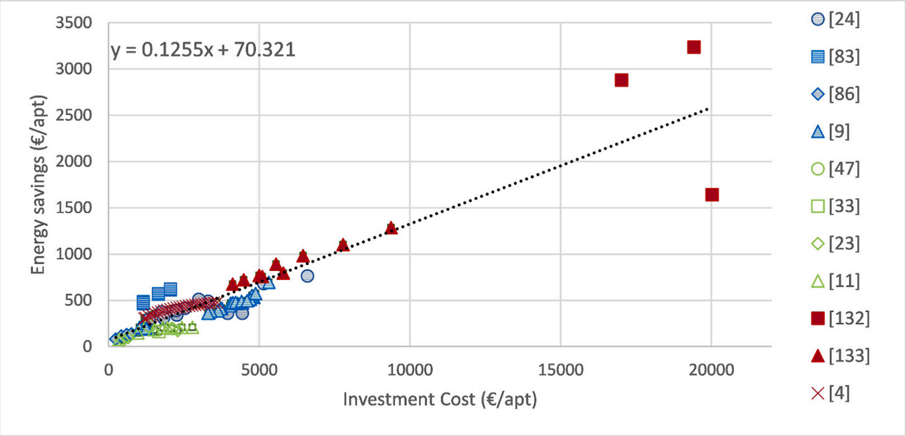

Fig. 4. Energy savings as function of investment cost in the analysed papers.

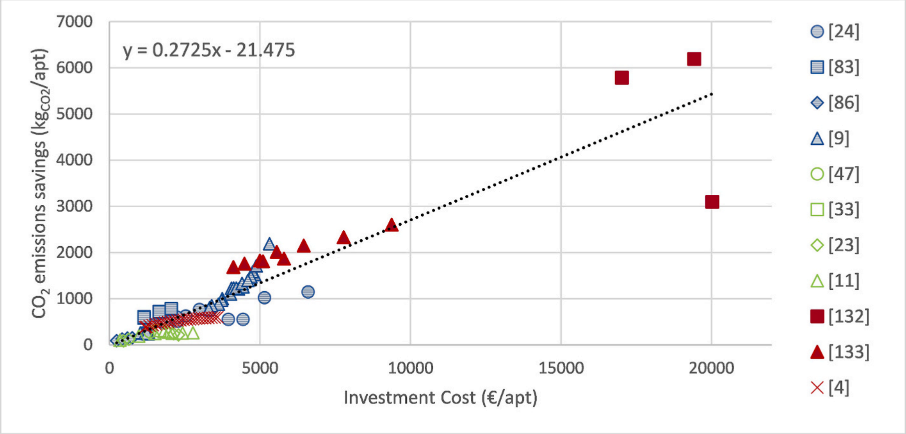

Fig. 5. CO_{2eq} savings as function of investment cost in the analysed papers.

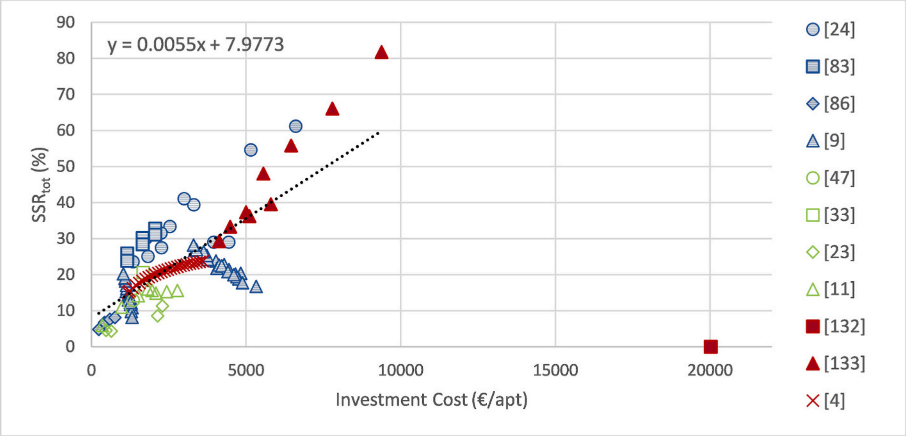

Fig. 6. SSR_{tot} as function of investment cost in the analysed papers.

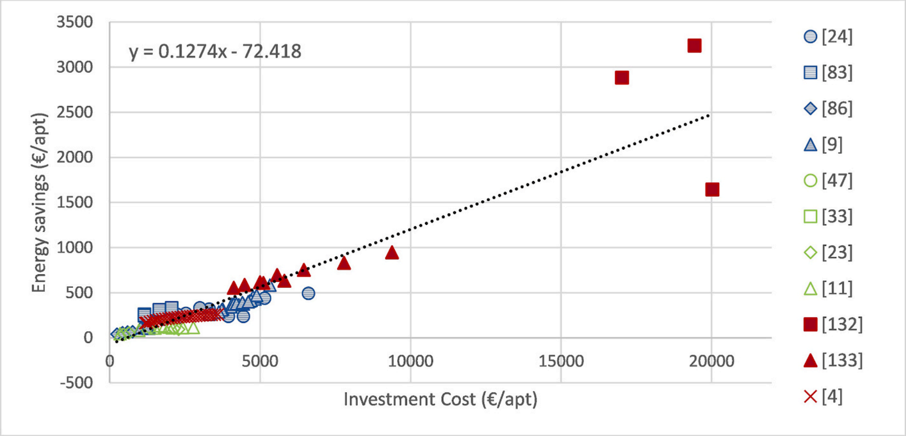

Fig. 7. Energy savings as function of investment cost in the analysed papers in VSC configuration.

time revealing the need to further explore the interactions between different typologies of actors, which can potentially promote or discourage citizens' willingness to participate.

Furthermore, REC emerges as a multi-criteria, multi-stakeholder decision problem, which has to take into account different trade-offs and preferences at these two multi-dimensional levels. For instance, the relationship between the distribution system operator and the civil society is usually designed to minimise and prevent the inversion of energy flows, rather than to optimise the bidirectional efforts of the two actors. Here, another research trend could be identified in the design of sustainable business models, able to exploit the desirability of solutions from the trade-offs between the parties' objectives.

It is clear from this review that participation in RECs is most often explained through the economic dimension. However, there are several other dimensions that are also taken into account by analysts and REC members. Environmental concerns and the goal of reducing

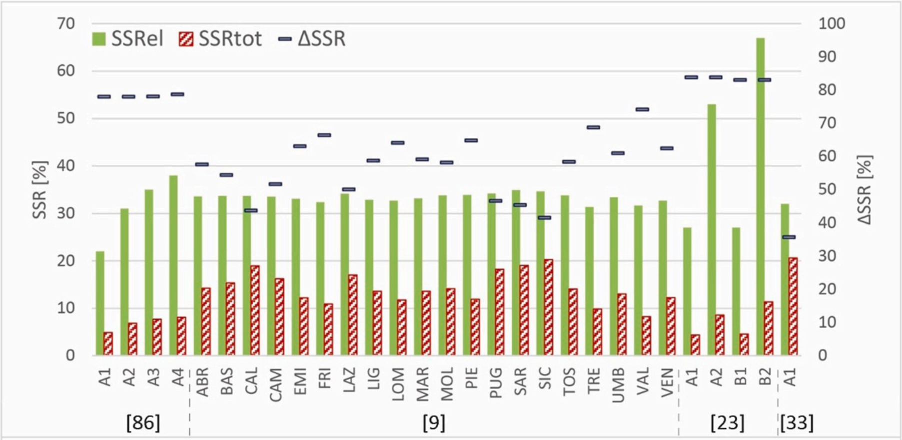

Fig. 8. Variation of SSR_{el} as reported in the studies, and SSR_{tot} recalculated according to equation (1).

environmental impacts are among the most important reasons for participation, albeit secondary to cost savings, along with reasons of self-sufficiency and energy security. Transparency of data and management, as well as bridging the knowledge gap, are also important for participation in the community. The development of RECs over time is characteristic of only part of the approaches used to study the subject, as researchers have mostly focused on feasibility. Feasibility over time could be another important avenue of research, considering the different times at which such experiences could start to work and how they could interact synergically with each other. Moreover, the choice of different solutions at different times could lead to sub-optimal or even negative outcomes for certain stakeholders (e.g. a large penetration of distributed generation from unpredictable renewable sources followed by a reduction in energy demand, leading to an increase in the production/consumption mismatch). In this sense, a well-established multi-stakeholder preference assessment framework may be needed to evaluate the feasibility of this promising instrument and to monitor its effectiveness throughout its life cycle.

The authors acknowledge some limitations in the scope of the analysis carried out, for example, a specific exploration of the business models adopted, as well as the evaluation of internal organisation strategies or financial benefits and burden redistribution, could provide further insights in the academic production on RECs, benefitting the synergies between actors and supporting policy makers in producing tailored solutions. These extensions of the horizon of analysis will be further explored in future studies.

An useful extension of the present study would be to include feasibility studies located in other countries, in order to compare the performance of RECs in different locations, as well as to include those entities aligned with the European definition that are currently being established and for which no data are yet available. Such an extension could provide an interesting opportunity to evaluate different business models, as well as redistribution mechanisms and economic feedback within them. Furthermore, broadening the scope of the scale of the analysis to include other uses (e.g. mobility) or other actors (e.g. municipalities, industry, tertiary, commercial, etc.) could represent a further optimisation to achieve higher decarbonisation targets at the urban scale. Finally, as the evaluation of the social benefits of RECs remains an unresolved issue, an agreed evaluation framework would be required to better design the establishment of RECs in line with the idea of a just transition.

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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Data availability

Data will be made available on request.

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