

Systematic Review of Software and Algorithms for the Implementation of Renewable Energy Communities (RECs)

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Abstract

Renewable Energy Communities (RECs) have gained traction in recent years as key instruments for the democratization of energy systems and the promotion of localized, sustainable energy production and consumption. The implementation of RECs has been underpinned by a variety of software programs and algorithms. This paper presents a systematic literature review of such methods following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology; moreover, following the PRISMA nomenclature, the review includes 420 reports, grouped into 311 unique studies, evaluating the literature according to REC development phases, methodological approach, software functions, openness, interoperability, and decision-support capabilities. Results show that most contributions focus on the modelling phase, specifically feasibility study and REC design, while stakeholder engagement, construction, and long-term operation remain less developed. Comprehensive software programs are mainly available for simulation and techno-economic analysis, whereas tools developed specifically for REC operation, monitoring, energy sharing, or decision support are often prototypes or case-specific implementations. These findings provide guidance for researchers, REC developers, policymakers, and community stakeholders seeking to select, improve, or regulate digital tools for RECs.

Keywords: Renewable Energy Community (REC); software; algorithms; energy transition; framework; digital tools



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1. Introduction

The global energy landscape is undergoing a fundamental transformation, driven by the need to address the growing climate crisis, reduce the reliance on fossil fuels, and ensure affordable, secure, and clean energy for all [1]. As one of the most energy-consuming sectors, the built environment accounts for 40% of global energy use and for 33% of global CO₂ emissions, indicating the need for better management and design of cities [2].

The United Nations explicitly stressed the importance of higher standards of urban living through the definition of the Sustainable Development Goal (SDG) 11: “Sustainable cities and communities”, part of the 2030 agenda for sustainable development [3]. In addition to this, the European Union (EU) has committed to achieving climate neutrality by 2050 as explicated by the European Green Deal [4] and enshrined in the European Climate Law [5]. These bind the EU to reach net-zero greenhouse gas (GHG) emissions through

strategies such as investments in green technologies but also a reformation of the energy markets [6].

In this context, Renewable Energy Communities (RECs) have emerged as a vital model for decentralized energy generation and governance [7–10]. The norm [11] defines: “Renewable energy community means a legal entity: (a) which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity; (b) the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities; (c) the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits”.

These communities enable citizens, local authorities, small businesses and other stakeholders to jointly produce, consume, store, and share energy generated from renewable sources [12,13] such as solar, wind, and biomass. By fostering local engagement, RECs offer an inclusive and democratic approach to the energy transition, creating not only environmental but also social and economic benefits [14–16].

The European Union has been at the forefront of promoting energy communities as part of its climate and energy policy. The Internal Electricity Market Directive (EU) 2019/944 [17] and the updated Renewable Energy Directive (EU) 2023/2413 [18] (RED III), previously REDII [11], provide a legal framework for the establishment and operation of RECs and Citizen Energy Communities (CECs).

These directives aim to empower citizens, local authorities, small businesses and other stakeholders to participate in the clean energy transition, improve energy efficiency, and support the goals of decarbonization. RECs are thus positioned as key enablers of the EU’s broader objective of achieving climate neutrality by 2050 [19–25]. According to recent estimates, half of European citizens could be involved in renewable energy production by mid-century, supplying up to 45% of the EU’s energy needs [26].

However, realizing the potential of RECs is not without challenges. Implementing and managing a community-based renewable energy system involves navigating complex technical, regulatory, and social landscapes [27]. Communities must be able to integrate Distributed Energy Resources (DERs) [28] such as photovoltaic panels (PV), wind turbines, batteries, and Electric Vehicles (EVs) into local distribution grids. They must also coordinate energy production and consumption among multiple actors with varying roles [29–31], such as prosumers (who both produce and consume energy), consumers, and energy service providers. Beyond physical infrastructure, RECs also require effective governance structures, transparent financial mechanisms, and robust community engagement [32–36].

To address these challenges and enable the scalable deployment of RECs, digital tools play an increasingly essential role [37]. From the initial design and simulation of energy systems [38–42] to real-time monitoring [43,44], energy trading [45–48], demand response [49,50], and user engagement [51], digital technologies provide the foundation of RECs. A well-designed software ecosystem can automate many aspects of REC operation, facilitate decision-making, optimize energy flows, and support compliance with regulatory frameworks [52,53].

The Internet of Things (IoT) [54], Artificial Intelligence (AI) [55], and blockchain [56–58] have expanded the range of tools available to energy communities [59]. Real-time monitoring is possible thanks to smart meters and sensors that collect granular data on energy usage and generation. Energy management systems [60], then, process this data to balance supply and demand, predict consumption patterns, and enable trading of surplus energy, potentially up to peer-to-peer (P2P) applications [61,62]. Comprehensive software pro-

grams also provide user interfaces that allow community members to visualize their energy data, vote on decisions, and manage investments [63]. Moreover, cloud-based services offer scalability and integration with national grid operators or aggregators, while edge computing enables real-time decision-making at the local level [59,64].

Proprietary simulation environments like MATLAB/Simulink [65], HOMER Energy [66], and TRNSYS [67] are widely used for planning, feasibility studies, and techno-economic optimization of community energy systems. Moreover, open-source software programs have also become an important enabler for RECs, particularly in facilitating transparency, customization, and collaboration [68]. Tools such as OpenEMS [69], Energy-community.jl [38], and Local Energy Communities software kits [70] allow communities to model and manage their own energy systems without relying solely on proprietary solutions. All these software programs are especially valuable during the early stages of REC development, where decisions about system sizing, component selection, and load management can significantly influence long-term performance and viability [29].

Beyond technical tools, software also supports the social and organizational aspects of RECs [53,71]. Tools that enable participatory governance, such as digital voting systems [71], citizen feedback portals [72], and communication tools [73], can increase community engagement and trust. Financial management tools help track investments [74,75], revenues from energy sales [76,77], and operational costs [78], which is essential for transparency and long-term sustainability. Education and gamification tools [79,80] can help raise awareness and encourage behavioural changes that reduce energy consumption and improve efficiency.

The importance of data analytics in RECs cannot be overstated. Data generated from smart meters, weather forecasts, energy storage units, and user behaviour [81] must be processed to produce actionable insights [82]. Advanced analytics, including machine learning algorithms [68,83,84], can optimize energy distribution, detect anomalies, forecast renewable generation, and even recommend energy-saving behaviours to users [49,85]. Energy communities that integrate such capabilities into their operations are better positioned to reduce costs, increase reliability, and achieve greater autonomy from external energy suppliers [86].

Nonetheless, several gaps remain in the current landscape of comprehensive software for RECs [37,52,53]. Many available solutions are fragmented, limited in scope, or tailored to specific regional policies. Interoperability among tools, systems, and devices remains a significant challenge [87]. Furthermore, user-friendliness and accessibility are often overlooked [88], making it difficult for non-expert users to engage meaningfully with technical tools. There is also a lack of standardization and harmonization across tools, which can hinder the replication of successful REC models in different contexts [89].

In light of these challenges and opportunities [90], there is a growing need to systematically evaluate, categorize, and develop software solutions that cater, specifically, to the needs of renewable energy communities [71]. Such tools must be reliable, adaptable, and aligned with both technical requirements and social values [91]. Ideally, they should support the full life cycle of a community energy project—from ideation and planning to deployment, operation, and scaling [71]. Moreover, they should be designed to support citizen empowerment, energy justice, and environmental sustainability [92].

The novelty of this work lies in its comprehensive, systematic approach to mapping and evaluating digital tools for RECs, bridging technical functionality with social and environmental considerations. Unlike previous reviews [29,37,71,89], it catalogs available software and critically assesses their inputs, outputs, strengths, limitations, and applicability across the full project life cycle, highlighting emerging trends and persistent gaps. This paper aims to address this need by providing a systematic review of the current landscape

of digital tools for RECs following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart [93]. The primary objective of the review is to identify, classify, and evaluate digital tools that are specifically designed for the planning, implementation, and operation of RECs. These tools are classified according to the type of analysis they support and their primary role in the implementation of RECs.

By focusing on the intersection of community energy and digital innovation, this work contributes to the broader discourse on sustainable energy transitions. The goal is to provide a reference point for researchers, REC developers, policymakers, and community stakeholders seeking to implement, improve, or scale RECs through the strategic use of digital tools. As energy transitions continue to unfold at the local level, the development and deployment of robust, inclusive, and adaptable digital solutions will be critical to achieving a resilient and equitable energy future.

2. Materials and Methods

To identify relevant literature on digital tools supporting RECs, the PRISMA [93] checklist and guidelines have been utilized.

To gather relevant literature, a comprehensive search was conducted across scientific databases, including Scopus [94], IEEE Xplore [95], and ACM Digital Library [96]. The search included peer-reviewed journal articles, conference proceedings, and relevant institutional reports published between 2019 and 2025. The time range was chosen following the publication of the Renewable Energy Directive II (RED II) [11], released in December 2018, which formally introduced RECs as legal entities. Publications before 2019 (590 documents) were therefore excluded, as they generally do not address RECs in the current regulatory or conceptual framework. Nonetheless, earlier works were briefly reviewed to ensure that no seminal studies or widely cited foundational concepts were omitted. This verification confirmed that pre-2019 publications mainly focus on collective energy initiatives or local energy systems without explicitly framing them as RECs under RED II [11].

The final database searches were run on 12 February 2026. The studies have been searched based on a precise query in order to tackle the topic of RECs together with possible digital tools. The literature search was conducted by screening the titles, abstracts, and keywords of publications for references to renewable energy communities and associated computational or analytical tools. This conceptual search logic was used across all databases considered, but the syntax was adapted to each platform.

The full search logic was applied to Scopus and translated to the corresponding advanced-search query: TITLE-ABS-KEY (("renewable energy communit*") AND ("software*" OR "tool*" OR "platform*" OR "algorithm*" OR "analysis" OR "formulation*" OR "approach*" OR "mechanism*" OR "framework*" OR "model*" OR "simulation*" OR "optimization" OR "methodolog*" OR "decision support" OR "implementation") AND NOT ("governance" OR "polic*" OR "regulatory")).

For IEEE Xplore and ACM Digital Library, the search was done within Title, Abstract and Author Keywords for: ("renewable energy communit*") AND (software* OR tool* OR platform* OR algorithm* OR analysis OR formulation* OR approach* OR mechanism* OR framework* OR model* OR simulation* OR optimization OR methodolog* OR "decision support" OR implementation) NOT (governance OR polic* OR regulatory).

The exclusion of governance, policy, and regulation terms was introduced to preserve the engineering and computational focus of the review. Literature centred primarily on governance, policy, or regulation often addresses institutional arrangements, legal frameworks, participation models, or regulatory barriers, which would have broadened the scope of the review beyond digital tools. For these same reasons, the scope of this review

has been limited to the fields of energy, engineering, environmental sciences, computer science, social sciences, mathematics, business, economics, and multidisciplinary studies. This restriction was imposed because the systematic review specifically focuses on scientific and engineering domains.

The resulting 1878 reports were manually screened based on their abstracts, and 1366 were excluded because they were either unrelated to the topic of RECs or not accessible. Following the PRISMA flow diagram in Figure 1, the review included 420 reports, which were grouped into 311 unique studies as shown in Table S2 in Supplementary Materials. This nomenclature follows the PRISMA guidelines which distinguish a report as “A document (paper or electronic) supplying information about a particular study. It could be a journal article, preprint, conference abstract, study register entry, clinical study report, dissertation, unpublished manuscript, government report, or any other document providing relevant information”. Instead, a study is defined as “An investigation, such as a clinical trial, that includes a defined group of participants and one or more interventions and outcomes. A “study” might have multiple reports. For example, reports could include the protocol, statistical analysis plan, baseline characteristics, results for the primary outcome, results for harms, results for secondary outcomes, and results for additional mediator and moderator analyses”. The studies and the related reports are listed in Table S1 in the Supplementary Materials.

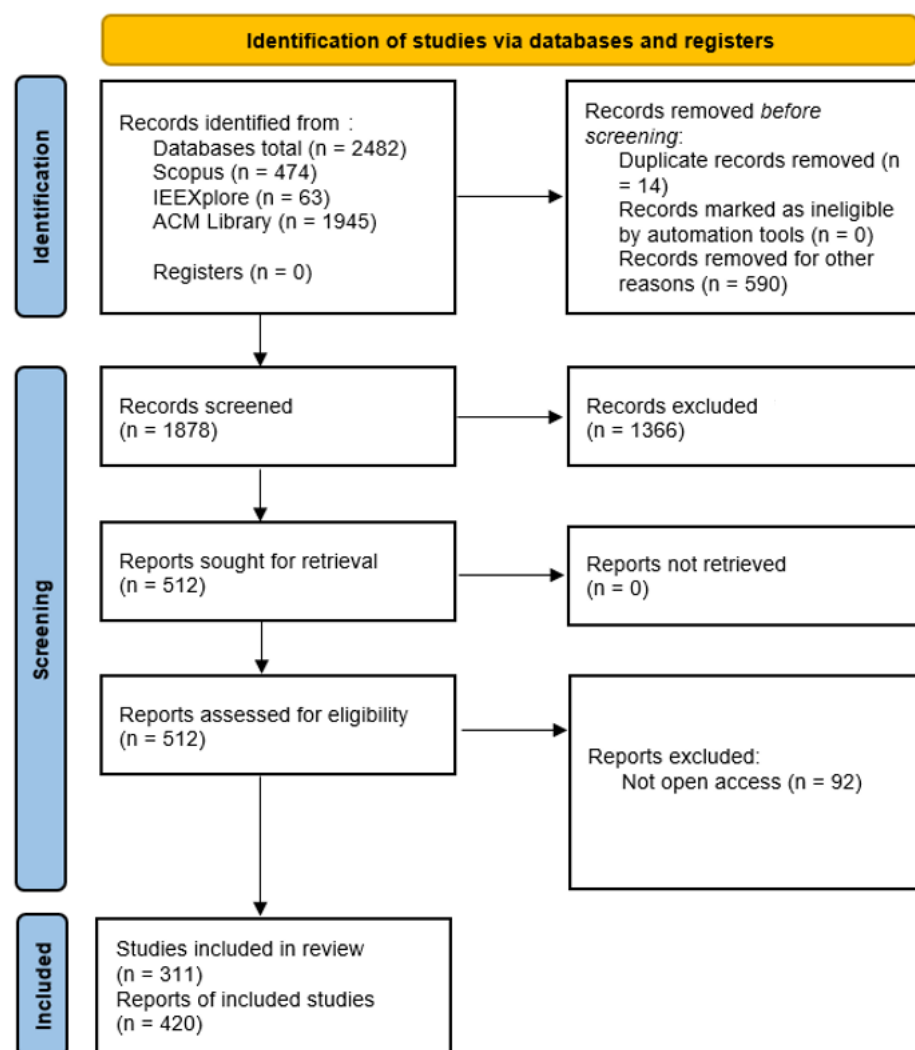


Figure 1. PRISMA flow diagram of systematic record selection for the topic of RECs.

Records were analysed first by title, abstract, and keywords and then, when necessary, by the accessible full text. Screening, data extraction, and first-pass classification were performed by one reviewer, while ambiguous eligibility decisions, category definitions, and the final synthesis were discussed with the co-authors during manuscript development. Automation tools were not used to make inclusion or exclusion decisions. Generative-AI tools were used only as auxiliary support for keyword exploration and text drafting, as declared in the acknowledgements; the authors checked and edited the output and retained responsibility for all decisions and interpretations.

Data was extracted into a structured matrix. For each included report, the extracted variables included bibliographic information, publication year, source type, subject area, type of analysis, REC development phase, methodological approach, software or algorithm name where available, input data, output data, open-source status where reported, decision-support function, strengths and limitations.

For consistency, the methodological approaches categories were defined before data extraction. Specifically, they are distinguished among conceptual frameworks, mathematical formulations, algorithmic implementations, and comprehensive software programs, explained in detail in Section 4.2. These methodological approaches together are referred to as tools in this review.

Interoperability was coded as the reported or documented ability of a tool to exchange data or operate together with other systems, datasets, modelling environments or monitoring infrastructures. Specifically, it refers to semantic interoperability as defined by the European Interoperability Framework (EIF) [97].

Open-source status was assigned only when the reviewed report or cited software documentation explicitly stated that the tool was publicly available [98]. Decision-support function was assigned when the tool provided outputs intended to guide planning, design, operation, management, or policy decisions, rather than only producing quantitative results [99].

When a report addressed more than one REC phase or function, multiple categories were assigned. Borderline cases were resolved using the dominant purpose of the contribution. Ambiguous cases were discussed among the co-authors before final classification. Missing or unclear information was coded as “unknown” or left blank rather than inferred. Reports were eligible for each synthesis when the extracted variables matched the relevant synthesis category, for example, type of analysis, REC phase, or software/algorithmic implementation.

The review used descriptive and qualitative synthesis. Counts and percentages were calculated from the coded extraction matrix, and each report could contribute to more than one category when they addressed multiple REC phases or methodological functions. Reports addressing multiple REC phases or methodological functions were counted in all applicable categories.

Results were tabulated and displayed using the PRISMA flow diagram, frequency tables, comparison matrices, pie charts, and thematic figures. No meta-analysis was conducted because the included literature was methodologically heterogeneous and did not report comparable intervention outcomes or common quantitative effect estimates. Heterogeneity was explored descriptively by grouping reports according to REC phase, analysis type, methodological approach, and software or algorithm family. No statistical sensitivity analysis was conducted.

A formal study-level risk-of-bias appraisal was not performed because the review does not synthesize clinical, epidemiological, or intervention-effect outcomes. Instead, the synthesis records the methodological strengths, limitations, input requirements, outputs, and applicability constraints of the identified comprehensive software program and

algorithmic implementations. For the same reason, no effect measures, reporting-bias assessment, or certainty-of-evidence grading framework were applied. These PRISMA items are therefore reported as not applicable to the descriptive systematic mapping design used in this review.

The 420 reports included in the systematic review have been initially analysed based on their subject area. Each report has been classified based on the type of analysis identified either as technical, environmental, economic, or social. Along with this, each field of research covered by the reports has been registered in order to highlight which ones were less, or not at all, deepened. A parallel classification was developed on the phase of the REC development that each report tackles. The phases identified are (1) stakeholders' engagement, (2) modelling phase, (3) construction phase, and (4) operating phase. The methodologies utilized in each of these were analysed to understand patterns or correlations.

Specifically, the comprehensive software programs and algorithmic implementations identified are categorized according to the specific stage of the REC life cycle in which they are applied and the type of analysis they support. For each, its key inputs and outputs, main functionalities, strengths, limitations, and applicability in different contexts are reported. This structured approach allows for a clear comparison across tools, highlighting gaps in current solutions and identifying emerging trends, such as the integration of artificial intelligence, cloud-based platforms, and participatory decision-support features. By systematically mapping the landscape of comprehensive software programs and algorithmic implementations for RECs, this work provides a practical reference for researchers, practitioners, and community stakeholders seeking to implement or improve community energy projects through digital innovation.

3. Scope of REC-Related Literature

The records have been initially analysed based on different areas of analysis, showing the multisectoral nature of the topic. Four different types of analyses have been identified: technical, environmental, economic, and social. Technical analyses include those studies that focus on the infrastructure and technologies used in RECs and aim to assess system design, energy efficiency, interoperability, and scalability [37].

Environmental analyses, instead, examine the ecological benefits of RECs, specifically reductions in GHG emissions, and often include Life Cycle Assessments (LCAs) and environmental impact evaluations [100].

Financial viability, cost savings, investment models, tariff structures and return on investment are studied in economic analyses [101–113].

Social analyses, finally, deepen community engagement, social acceptance and behavioural change in the community where the REC is implemented or could be developed [114–118].

Considering all four previous macro-areas, 40 different topics have been further identified.

Stakeholder engagement is, instead, the main topic of social analyses and is often studied accounting for energy poverty [119,120], energy feedback [72], and risk assessments [121–125]. This focus reflects the understanding that the success of RECs depends not only on technical and economic factors, but also on social awareness and an active and sustained involvement by community participants [92]. Social analyses therefore investigate the motivations, barriers, and behavioural dynamics that shape engagement in RECs [51,63,73,79,80,88,126–137].

Among the 40 topics, only two of them focus on environmental analyses specifically aimed at quantifying GHG reductions [38,100,133,138–143] or conducting LCA [144–147] within the context of RECs. This indicates that environmental performance remains an

under-explored dimension in REC-related research, despite its relevance for assessing the overall sustainability of these initiatives.

The biggest share of topics, 17 out of 40, fall under technical analysis. Specifically, Figure 2 presents the various technical topics addressed in the reviewed studies, categorized by the number of publications. To facilitate understanding, the topics have been grouped by colour according to thematic similarities. The REC Development group (light blue) gathers studies on system optimization and design, while Energy Flow (orange) and Management of REC (green) cover operational aspects such as demand profiling, supply-side flexibility, and energy storage scheduling. Mechanical Systems (dark blue) focuses on thermal regulation and HVAC strategies. Finally, the Renewable Energy Sources category (yellow) consolidates all generation technologies, merging the dominant PV systems with wind, biomass, and hybrid solutions.

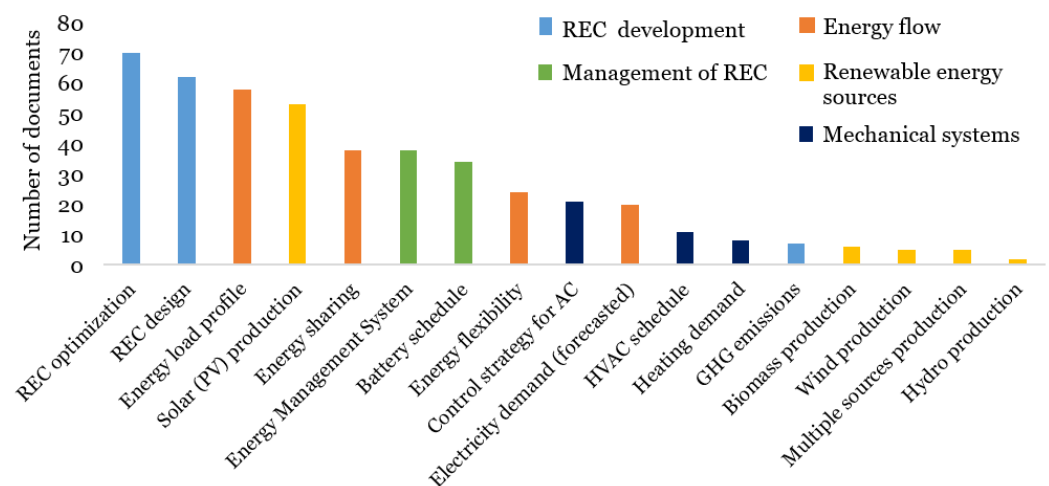


Figure 2. Number of technical analyses per topic.

According to Figure 2, the most extensively researched area concerns REC development, particularly the design and optimization, which highlights that current research is oriented toward the planning and structuring of community-based energy systems. Within RECs, the mechanisms of energy exchange among participants are heavily researched. This focus reflects the central role that energy flows, both within the community and with the external grid, play in the functioning and optimization of RECs. Specifically, topics such as the implementation process of energy sharing models [141,148–154], load consumption profiles [49,155–159], assessment of community energy uses [149,160–164], and the quantification of energy effectively shared among members [49,148,165–172] are frequently addressed in the literature. These aspects are critical for ensuring the technical viability and economic efficiency of RECs, as they directly influence system design, energy balancing, and the potential benefits distributed among participants.

Moreover, in this systematic review, it has been decided to distinguish the various renewable energy sources identified in the literature for electricity production. Solar energy, in particular exploited by PV systems, emerges as the most extensively studied, particularly in relation to electricity production potential [38,119,153,173–179] and system sizing [42,144,145,162,180–182] within RECs. This reflects the widespread adoption and accessibility of PV technology, especially in residential and urban contexts.

In contrast, renewable energy production from other sources, such as wind [42,49,144,145,181,183], biomass [184–187], hydro [188–190], or a combination of multiple sources, Refs. [157,185,191–193] are considerably less represented. This indicates a research gap in the diversification of energy generation strategies within RECs. This predominance reflects not only the widespread adoption and accessibility of PV technology

but also its strong suitability for urban and residential environments, where available space, regulatory constraints, and installation feasibility make PV the most realistic renewable option in most cases [194].

Publications addressing management of REC (e.g., Energy Management Systems [60,164,195–197] and battery scheduling [160,173,198–202]) occupy a mid-range position, showing the relevance of predictive and supervisory control in community energy systems.

Finally, 40 reports address the integration of mechanical system schedules, such as heating, ventilation, and air conditioning (HVAC) [161,174,175,181,203,204], and advanced control strategies [81,165,205,206]. This indicates limited consideration of total household energy demand despite its critical role in self-consumption efficiency, accurate load balancing, and overall system efficiency in community energy configurations.

4. Results

4.1. RECs Development Phases

RECs involve various development phases, from initial design to continuous management [101,207]. Through this systematic review, multiple phases have been identified for the development of RECs, and the reports have been categorized based on the phase (or phases) they tackle. Specifically, the phases identified throughout the literature and detailed further in the following subsections are (1) stakeholder engagement, (2) modelling phase, (3) construction phase, and (4) operating phase. The process begins with stakeholder engagement, detailed in Section 4.1.1, ensuring community involvement and acceptance from the earliest stages. This input informs the modelling phase, highlighted in Section 4.1.2, which includes four sequential steps: pre-feasibility study, feasibility study, REC design, and refinement. These stages assess technical and economic viability, define system configurations, and refine models to achieve optimal performance and community alignment. The construction phase follows in Section 4.1.3, during which the REC is physically built, the system configuration is verified, and necessary adjustments are made, for example, resolving discrepancies between design assumptions and practical constraints. Data is also collected to support the validation of design assumptions. The project then transitions into the operating phase, Section 4.1.4, encompassing ongoing management and operational optimization to ensure long-term efficiency, adaptability, and stakeholder satisfaction. Loops between stakeholder engagement and modelling, and between optimization and data gathering, ensure continuous improvement and community development. The workflow for the implementation of RECs is visible in Figure 3. The dotted lines represent possible cycles back to previous stages due to updates or changing of data.

Figure 4 presents the distribution of research efforts across the different phases of REC development in this systematic review. The analysis highlights a strong focus on the modelling phase (53%), which dominates the literature. This predominance is unsurprising given that only a limited number of RECs are currently active [29]. For this reason, most contributions concentrate on energy, economic and environmental assessments based on simulated REC configurations. In relation to this, while aspects concerning the construction phase remain limited (7%), the operational phase occupies a significant portion of the literature (29%). This focus is driven by the inherent complexity of REC management, which necessitates advanced control systems to ensure configuration flexibility and effective energy matching [29]. Consequently, the prevalence of simulated configurations [60] serves a strategic purpose: it allows for the development and validation of energy flexibility and remote management protocols in a controlled environment, essential for sectors where such integration is still emerging.

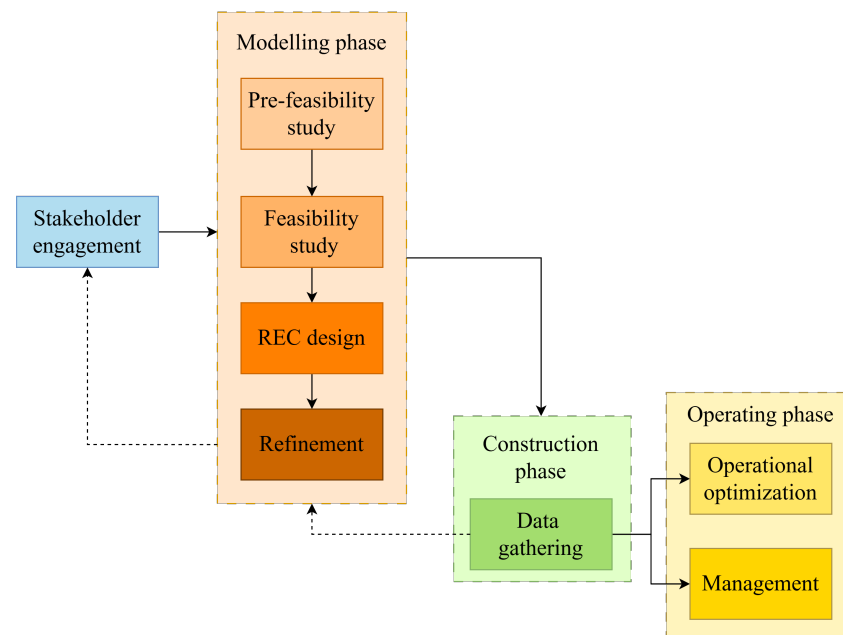


Figure 3. General workflow for the implementation of RECs.

Finally, stakeholder engagement (10%) is the least covered phase, despite being a crucial factor for community acceptance, governance, and long-term sustainability of RECs [51]. Unlike technical or economic aspects, stakeholder engagement relies on qualitative factors such as trust, participation, and local governance, which are challenging to capture through conventional analytical or optimization methods [208]. Moreover, the lack of surveys and empirical studies limits the availability of data to systematically assess community behaviour and attitudes [89].

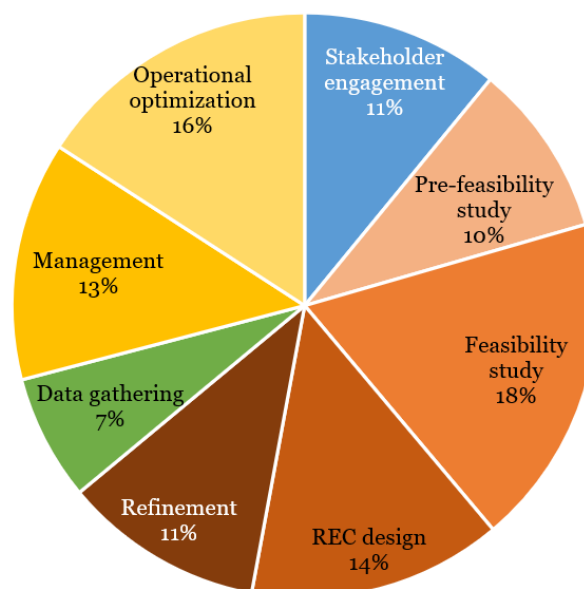


Figure 4. Pie chart showing the proportion of reports focusing on each phase of RECs.

4.1.1. Stakeholders Engagement

The engagement and participation of stakeholders constitute a foundational phase in the establishment and long-term success of RECs [51,72,129]. Socially, RECs contribute to strengthened community cohesion, increased democratic participation, and the cultivation of empowered citizens capable of influencing energy decisions [134,209–211]. RECs are

designed to empower individuals and other stakeholders to become active agents in the energy transition, fostering a shift toward more democratic, inclusive, and resilient energy systems [79,212,213]. RECs are defined as autonomous legal entities [11] based on open and voluntary participation, governed effectively by members or shareholders who are located in proximity to the renewable energy projects they own and manage [129,214,215]. These members may include individuals, small and medium-sized enterprises (SMEs), or local authorities [130]. Given this heterogeneity of actors, terminologies for their involvement differ across the literature: the phase is variously conceptualized as “social analysis” [216], “social accounting” [217], or “social dimension” [218], while others emphasize “user engagement” [219], “participatory processes” [220], or “community involvement” and “participation” [221–223]. To harmonize these varied perspectives with the regulatory scope defined by REDII, this article adopts the comprehensive term “stakeholder engagement”.

The objectives and mechanisms of this phase vary significantly across development stages of RECs due to its transversal and iterative nature within the REC lifecycle [51]. In the modelling phase, the primary focus is often pragmatic community construction: aggregating sufficient participation to achieve critical mass [224]. During this stage, engagement serves to mitigate specific barriers, such as trust deficits toward institutions [132] and financial constraints regarding upfront capital [63,136]. Literature suggests that targeted interventions, such as awareness-raising campaigns [129,225], community workshops [51], and the design of gradual participation pathways [134], are essential to lower entry barriers and secure initial buy-in.

Conversely, as the REC transitions into the optimization phase, engagement strategies must shift from recruitment to active management and behavioural alignment [88]. In this context, the objective becomes the synchronization of user behaviour with the technical requirements of the system, such as load shifting or flexibility provision [226–231]. To this end, advanced instruments including digital platforms [130], gamification techniques [80], and collaborative networks [126] are employed to sustain interaction. While successful engagement can lead to distinct social externalities, such as increased democratic participation and citizen empowerment [79,134,232,233], the primary driver often remains the functional viability of the project [51,72].

Despite being a fundamental pillar for the long-term success of RECs, stakeholder engagement remains one of the least represented areas in the literature, mainly due to the difficulty of modelling and quantifying social processes. Unlike technical or economic aspects, engagement relies on qualitative dimensions that are inherently complex to measure and integrate into optimization frameworks [51].

4.1.2. Modelling Phase

The modelling phase represents the technical foundation for the establishment of a REC. Although frequently categorized broadly as “system modelling” [234–236] or “energy planning/simulation” [140,237–239], this study adopts a granular approach to capture the full technical complexity of the process. As illustrated in Figure 3, the phase is structured into four sequential sub-phases: pre-feasibility study, feasibility study, REC design, and refinement. This sequence is designed to progressively refine the project, advancing from initial viability assessments to detailed system dimensioning and performance maximization.

The process typically begins with the pre-feasibility study, a phase frequently identified as “aggregation of users” [240–242], “profile modelling” [243,244] or “resource allocation” [245–247]. This phase, indeed, aims at identifying potential members and their role in the REC as consumers, producers or both (called prosumers) [80,248]. This report entails the aggregation of users, where stakeholders (i.e., households, businesses, and public entities) are selected to address the configuration of the community. When technical purposes

prevail, users are often chosen according to their energy profiles, consumption patterns, and proximity to shared infrastructure [224,249–254].

The results from the pre-feasibility study are then utilized in the following phase called feasibility study [100,145,255–258], aimed at locating the current state of the concerned site [248]. This phase requires a comprehensive assessment of regulatory, geographical, cultural, and political conditions [101], alongside an evaluation of existing legislation, local resources, and urban planning constraints that may influence project feasibility [76,259–262].

While often broadly categorized as “modelling” or “planning” in existing studies [247,263–265], this terminology creates ambiguity with the modelling phase defined above. Consequently, this next sub-phase is identified as “REC design” to specifically denote the selection and dimensioning of physical assets, such as PV arrays [266], wind turbines [49], or biomass plants [185], as well as integrating energy storage solutions [38] and energy-efficient building strategies [203]. These evaluations are guided by local climatic conditions, spatial constraints, and historical consumption data previously evaluated in the feasibility study.

Finally, the refinement phase represents a distinct and critical area of investigation within the modelling framework, often distinguished from standard design as “optimal sizing” [162,195,247,267–269] or “advanced energy simulation [168,206,236] or “optimization” [181,270–273].

Rather than a mere sequential step following the initial design, it constitutes an advanced optimization [274] that attracts significant research interest due to its potential to maximize benefits across technical, economic, environmental, and social dimensions [29]. In this sense, refinement is considered essential for enhancing the efficiency of RECs, moving beyond simple energy generation to strategic planning and operation that ensures viability and sustainability [89]. However, this stage may present multiple challenges such as high computational complexity due to large decision spaces [38], conflicting objectives (e.g., technical, economic, environmental, social) [144,275,276], and uncertainties in renewable generation, market dynamics, and user behaviour [165]. These complexities often necessitate multi-objective, heuristic, or stochastic approaches [39,41,226,277,278]. Furthermore, the practical applicability of optimization models is limited by data scarcity, privacy concerns [88], and the difficulty of representing human behaviour and comfort preferences [180,233].

4.1.3. Construction Phase

Once the REC is modelled, implementation proceeds to the construction phase [248]. This stage marks the transition from modelling and simulation to real-world application and serves as a crucial step for data gathering [279] and validation [280] of the design hypotheses. It provides the empirical foundation for evaluating the actual performance of the REC against its predefined technical, economic, environmental, and social objectives [37]. In the literature, this stage is not defined solely by the physical installation of renewable energy technologies, but encompasses the broader deployment of the requisite infrastructure for operation and management [128,281,282]. This includes the integration of smart metering devices [283], the establishment of data transmission networks [284], and the setup of monitoring protocols necessary for real-time observation [285]. This phase is fundamental for measuring, monitoring, and ensuring the sustainability, effectiveness, and fairness of the community [286]. Its overarching purpose is to confirm that the REC not only achieves its technical and economic targets but also fulfils its environmental and social mission, thereby reinforcing its legitimacy and resilience over time [100].

Moreover, data gathering encompasses several interrelated objectives. Indeed, it concerns the quantification of the initial operational outcomes and the subsequent verifica-

tion of alignment with initial design targets [286,287]. Moreover, complementary impact assessments evaluate the actual environmental, technical, and economic effects of REC operation [101]. Finally, the resulting data provide the basis for further optimization, allowing designers and operators to identify and address emerging barriers, limitations, and challenges, ultimately refining and consolidating the REC's initial design and performance [92].

4.1.4. Operating Phase

The operating phase is referred to in the literature [279,288–291] as the period in which the REC actively functions as an energy system, encompassing the real-time supervision, maintenance, and dynamic regulation of all installed assets [15]. It represents a crucial stage in the lifecycle of RECs that extends throughout the entire lifespan of the community [37]. It integrates two interrelated dimensions, identified in the literature as management [291–295] and operational optimization [283,296–299], that collectively ensure that RECs function efficiently, adapt to changing conditions, and remain aligned with its technical, economic, environmental, and social objectives [88].

In the management phase, the community is continuously monitored and evaluated through a comprehensive framework of indicators that capture environmental, economic, and social dimensions [300]. Energy performance is commonly assessed using indices such as self-consumption, self-sufficiency, and shared energy ratios [286,301], while economic performance is measured through revenues from incentive schemes [140], payback period, life cycle cost, net present value, and energy savings derived from self-consumption [302]. These metrics are often complemented by social and environmental evaluations, including assessments of carbon dioxide emission reductions, life cycle impacts, community satisfaction, and transparency in data sharing [72,145]. Broader social outcomes, such as community cohesion, knowledge democratization, mitigation of energy poverty, and inclusion of marginalized groups, also form essential dimensions of ongoing assessment [303].

Real-time data acquisition underpins this management process. Smart meters and digital monitoring platforms enable continuous tracking of shared energy flows, individual consumption, and production patterns [53,304]. These systems are increasingly integrated with blockchain-based platforms that enhance transparency, ensure data authentication, and enable secure peer-to-peer energy exchanges [61,305,306]. Remote management and monitoring are further supported by plug-and-play communication modules leveraging Low-Power Wide Area Networks (LPWANs) [131,307].

The operational optimization phase focuses on maximizing REC efficiency through advanced control and coordination strategies. Sophisticated Energy Management Systems (EMS) [60,72,88,131,302,308,309] and optimal control methods for shared assets, such as battery energy storage systems (BESSs) [199,298,310–320], are employed to balance generation and load, manage forecast uncertainties [279,321–326], and enhance energy sharing to reduce member costs. Demand Side Management (DSM) [37,327–329] and Demand Response (DR) programs [131] encourage users to shift consumption patterns, contributing to improved operational flexibility and efficiency [330–333]. These strategies can also deliver ancillary benefits, such as congestion management and grid support services [334]. Furthermore, Power-to-X applications—such as power-to-heat, power-to-vehicle, and power-to-gas—enable the effective use of surplus renewable energy, strengthening self-consumption and promoting cross-sectoral energy integration [327,335].

4.2. Methodological Approaches in REC Phases

To effectively plan, implement, and manage RECs, stakeholders increasingly rely on specialized comprehensive software programs and algorithmic implementations. These tools serve a variety of purposes, ranging from technical modelling and energy system

optimization to financial analysis, stakeholder engagement, and performance monitoring. They enable users to simulate scenarios, assess feasibility, optimize resource allocation, and support decision-making across all stages of a REC's life cycle. In this context, it is important to distinguish the four methodological approaches found in the literature: (i) conceptual frameworks, (ii) mathematical formulations, (iii) algorithmic implementations, and (iv) comprehensive software programs. It is therefore essential to classify the methodological approaches found in literature according to these four categories, as each reflects a distinct level of methodological maturity.

The conceptual framework refers to the theoretical structure that organizes the logic used to address the problem. It does not include mathematical formulations or operational details; instead, it provides an abstract representation of the underlying concepts and their relationships. Conceptual frameworks, indeed, represent the most foundational stage, providing the overarching theoretical structure and logic that guide the formulation of models but without mathematical formalization or operational detail.

Mathematical formulations are theoretical models made of equations and analytical expressions. Mathematical formulations constitute the stage where these ideas are expressed through formal models that remain theoretical and untested in practice.

Algorithmic implementations operationalize these formulations into executable routines, typically written in programming languages such as Python or MATLAB, to conduct simulations or numerical analyses. Algorithmic implementations occupy an intermediate position, indicating functional methods that have been translated into executable code but are not yet integrated into broader software systems.

Comprehensive software programs, by contrast, refer to mature, integrated, user-oriented applications that embed multiple coded algorithms within graphical interfaces or platforms, allowing for broader accessibility, reproducibility, and practical deployment. Comprehensive software programs represent the stage where mathematical formulations and algorithms have been fully implemented and operationalized into user-friendly tools.

This classification helps identify gaps between theory, implementation, and operational use, particularly highlighting areas where promising algorithms have yet to be incorporated into available REC comprehensive software solutions. The heatmap in Figure 5 illustrates the prevalence of methodological approaches across the different phases of REC development. The percentages represent the share of the specific methodological approach within that REC phase.

Stakeholder engagement activities are addressed overwhelmingly through conceptual frameworks (90%), confirming that this phase is still characterized by qualitative approaches rooted in participation, behavioural analysis, and community dynamics. Mathematical formulations appear only marginally (8%), typically in contributions that formalize stakeholder interactions or cooperative mechanisms, such as game-theoretic approaches [80,336,337]. Algorithmic implementations and comprehensive software programs remain almost absent at this stage. For these reasons, the stakeholder engagement phase is not included in further evaluations of algorithmic implementations or comprehensive software programs utilized in this phase.

Moving into the technical phases, the heatmap shows a pronounced shift toward algorithmic implementations, which dominate in pre-feasibility studies (52%) and reach their highest prevalence in refinement tasks (73%). This reflects the strong computational demand of scenario exploration and system optimization in RECs. Feasibility studies and REC design display more diversity. They combine conceptual approaches, mathematical formulations, and algorithmic implementations. However, the higher presence of comprehensive software programs (respectively 45% and 39%), indicates that they have been developed to support planning activities. Given that only a limited number of RECs are

currently operational, such comprehensive software programs have become essential for exploring multiple scenarios, assessing technical and economic feasibility, and guiding design decisions in a controlled, reproducible environment.

	Conceptual framework	Mathematical formulation	Algorithmic implementation	Comprehensive software
Stakeholder engagement	90%	8%	2%	0%
Pre-feasibility study	17%	14%	52%	17%
Feasibility study	10%	18%	28%	45%
REC design	16%	18%	27%	39%
Refinement	5%	11%	73%	11%
Data gathering	15%	12%	49%	24%
Management	20%	9%	62%	10%
Operational optimization	8%	18%	64%	10%

Figure 5. Heatmap of percentage distributions of different methodological approaches used across eight phases of RECs. Warmer colors (red/orange) indicate lower frequency percentages, while cooler colors (green) indicate higher ones.

Data-gathering activities, instead, show a majority of algorithmic implementations (49%), which is consistent with the increasing use of data processing, clustering, and analytical pipelines needed to support REC operation [338]. The same applies to management (62%) and operational optimization (64%), where computational workflows become central to monitoring, coordination, and real-time decision-making.

Taken together, the heatmap highlights a methodological gradient across REC-related research. Socially oriented activities remain grounded in qualitative, conceptual approaches, while modelling, refinement, and operations are strongly driven by algorithmic implementations or comprehensive software programs. Mathematical formulations maintain a steady but secondary presence across all phases, often acting as the bridge between conceptual reasoning and computational implementation. The relatively low presence of comprehensive software programs across most phases suggests that, despite significant methodological advances, the transition from research prototypes to widely accessible tools for practitioners is still limited in current literature.

In Appendix A, Table A1, all the comprehensive software programs found in this systematic review have been summarized with the phase of REC development they tackle, inputs, and outputs. Moreover, in Table A2, a matrix is shown with all the comprehensive software programs and algorithm implementations applied in this systematic review. The matrix shows applications and main characteristics of each to understand their input data, output data, open-source status where reported, decision-support function, strengths and limitations. Capabilities were not inferred unless they were explicitly described in the reviewed source or in the software documentation cited by the source.

Comprehensive Software Programs and Algorithmic Implementations

Building on the phases identified in the literature (stakeholder engagement, modelling, construction, and operation), this subsection provides an overview of the most common comprehensive software programs and algorithmic implementations associated with each stage. By examining their functionalities, degrees of openness, interoperability, and typical applications, the review aims to clarify how digital solutions contribute to REC design and implementation, as well as where limitations or methodological gaps persist. Because the stakeholder engagement phase is primarily addressed through qualitative methods, it falls outside the scope of this study and is therefore not considered in the subsequent analysis of

comprehensive software programs and algorithmic implementations. For a comprehensive breakdown of the adoption frequencies cited throughout this next section, refer to Table S2 provided in the Supplementary Materials. The percentages shown here are the share of the specific methodological approach (X) within that REC phase as shown by Equation (1).

$$X = \frac{\text{Number of reports with the specific methodology in that REC phase}}{\text{Total number of reports in that REC phase}} \times 100\% \quad (1)$$

Pre-feasibility study

In the pre-feasibility phase, various quantitative and software-based approaches are employed to identify potential REC members and assess their suitability based on energy behaviour and infrastructural context. Unsupervised clustering method [339–343] is the most common, appearing in 18% of the reports, reflecting their ability to segment prospective members based on empirical consumption patterns [224]. Linear programming [344], Multi-Objective Optimization (MOO) [247] and Artificial Neural Networks (ANNs) [345–349] are less prevalent (respectively 7%, 5% and 5% of reports) but provide complementary insights through optimization and forecasting tasks [49]. Among comprehensive software programs, the only one appearing with some regularity is the Load Profile Generator (LPG) [350] (4% of reports), primarily used when empirical data are limited, as it enables the rapid generation of synthetic load profiles. Taken together, these approaches support the characterization of potential REC members and the assessment of their prospective roles as consumers, producers, or prosumers [351–354].

Feasibility study and REC design

The feasibility study and REC design phases are closely interconnected and are therefore frequently analysed together, often through similar methodological approaches [355]. The feasibility study aims to characterize site-specific energy demand and supply potential while evaluating the viability of different regulatory, technical, and economic scenarios [258,356,357]. Building on these results, the REC design phase focuses on sizing the community's energy assets and defining its first operational configuration.

Literature shows that both phases are predominantly supported by comprehensive software programs, with the same solutions appearing as the most frequently adopted across the two stages. For this reason, here they are analysed together. Energy simulation software represents the most widely used category with a frequency of 36% in feasibility studies and 44% in REC design phase. They are able to model site-specific energy demand, generation potential, and system performance with high temporal and technical resolution [89]. These tools simulate energy flows using hourly or sub-hourly time steps, enabling the evaluation of different renewable generation mixes, storage configurations, and regulatory or tariff scenarios. Among these, TRNSYS [358] and EnergyPlus [359] are the most commonly applied, owing to their detailed component libraries and ability to perform dynamic thermal and electrical simulations [256].

GIS-based tools represent the second most common methodological approach in the feasibility phase and REC design, appearing in respectively 19% and 9% of reports. These tools play a critical role in spatially assessing local renewable resources, infrastructural constraints, and site suitability [235,360]. They enable multi-criteria spatial analysis, rooftop PV potential assessment, and visualization of energy-related geospatial datasets. PVGIS [361] and QGIS [362] are frequently employed to support geospatial data processing, infrastructure mapping, and the integration of environmental and regulatory layers. Despite their strengths, GIS-based approaches tend to simplify behavioural, socio-political, and temporal dynamics, which limits their ability to fully capture the complexity of REC feasibility [363].

Finally, linear programming [344] accounts for 9% and 10% of the methodological approaches reported in the literature for feasibility studies and REC design, respectively, offering a complementary optimization-based perspective. These models use structured decision variables, constraints, and objective functions to identify optimal energy system configurations under site-specific conditions [364]. They are commonly applied to size renewable energy and storage assets, optimize power flows among community members, and minimize overall system costs. Within this category, mixed-integer linear programming (MILP) [365] emerges as the most widely employed optimization algorithm, due to its ability to model discrete decisions, such as asset installation choices or on/off operation states, alongside continuous variables like energy flows [366]. While linear programming and MILP provide mathematically transparent and reproducible frameworks, they depend on extensive and accurate input data and remain limited in representing non-linear or stochastic system behaviours, as well as qualitative aspects such as governance, cultural acceptance, or regulatory uncertainty [367].

Refinement

The refinement of the REC design serves to identify the configuration that best aligns with the established performance objectives. In the refinement phase, algorithmic implementations prevail over comprehensive software programs Figure 5, highlighting the lack of specialized tools. The landscape of algorithms utilized in this phase in the literature is characterized by significant fragmentation. The most frequently adopted approach is the Multi-Objective Optimization (MOO) method [368] (23% of reports). Unlike single-objective strategies that focus on maximizing a sole metric (typically economic), MOO explicitly addresses conflicting goals (such as minimizing costs while simultaneously lowering emissions), allowing RECs to navigate trade-offs between sustainability, technical feasibility, and fairness [203,369]. In most studies employing MOO, the process is associated with a final Pareto approach. Instead of yielding a single optimal point, this method generates a set of trade-off solutions where improving one objective inevitably worsens another [199], empowering decision-makers to select the configuration that best fits their specific priorities.

Alongside MOO, deterministic methods represent a substantial portion of the research, specifically linear programming (LP) (14%) [367] and mixed-integer linear programming (MILP) [370] (11%). These approaches are particularly valued for their ability to handle precise mathematical constraints, with MILP being essential for modelling discrete investment decisions, such as the binary selection of specific assets.

Data gathering

After the optimization phase, the selected REC configuration is implemented in practice, and a dedicated data-gathering phase begins to verify whether real-world performance aligns with the goals established during the modelling phase. In this stage, algorithmic implementations play a crucial role in systematically collecting operational data, structuring it, and comparing measured values against the outcomes predicted by simulation models. This verification process is essential for assessing the consistency between expected and actual energy flows, economic returns, and environmental impacts [298].

The most commonly employed algorithmic implementations in this phase include mixed-integer linear programming (MILP) [365], numerical modelling [371], and stochastic programming [372], each appearing in 5% of reports. MILP formulations are frequently used to re-optimize or validate operational schedules by incorporating real measurements into the optimization framework [373]. This allows researchers to assess how closely the implemented REC configuration adheres to the theoretically optimal dispatch strategy under real-world constraints [272].

Numerical models, on the other hand, are used to reproduce the physical behaviour of energy flows within the REC [374]. These models rely on mathematical representations of generation, storage, and demand components to quantify discrepancies between simulated and observed performance. Their flexibility makes them suitable for scenario testing, sensitivity analysis, and benchmarking system behaviour against initial assumptions [374].

Stochastic programming adds a layer of robustness by explicitly accounting for uncertainties in renewable generation, energy prices, and user demand. Through probabilistic formulations, it enables the evaluation of REC performance under a wide range of plausible operating conditions [279]. This helps identify whether deviations from expected performance are due to modelling inaccuracies, unforeseen variability, or structural limitations in the system design. These methods enable the analysis of complex system behaviours under varying conditions, support the identification of deviations from expected performance, and facilitate the understanding of uncertainties inherent in REC operation [375].

While algorithmic implementations dominate the data gathering phase, several energy simulation software programs also appear in the literature, though less frequently. Notable examples include SIMUL-REC [376], Web-GIS platforms [377], Emoncms [378], and EnergyCommunity.jl [379]. These tools primarily support data visualization, monitoring, and integration with measurement devices, complementing the more advanced algorithmic techniques used for quantitative assessment and performance validation [53]. Their limited presence in this phase largely reflects the technical complexity and heterogeneity of REC data acquisition, which makes it challenging to provide end-users with streamlined, generalizable comprehensive software programs [280].

Management

The management phase within the operating stage of RECs focuses on the coordinated operation of energy assets and the execution of energy-sharing strategies [380–382]. In the management phase of Renewable Energy Communities, the literature shows a strong reliance on algorithmic implementations to support real-time decision-making and operational control [298,320,383–387]. Among the most frequently adopted approaches, MILP [365] remains the dominant method (12% of reports), particularly for optimizing day-ahead scheduling, energy sharing, storage dispatch, and cost-minimization under operational constraints [388–390]. More recently, data-driven and adaptive control paradigms have gained traction. These include Reinforcement Learning (RL) [391] (4% of reports) which enables autonomous and iterative improvement of operational policies based on real-time feedback [205,392]. Moreover, ANN-based models (4% of reports) [345] support short-term forecasting of loads, PV production, and electric vehicle charging behaviour [160,393]. Additionally, MOO [368] (4% of reports) provide a framework to simultaneously balance competing REC goals, such as economic savings [394–396], carbon reduction, energy autonomy [397], and fairness among members [398], offering a more holistic approach to community operation [399,400].

Building on these methods, digital twin (DT) technology is increasingly recognized as a strategic enabler for advanced REC management [88,401]. A DT creates a continuously updated virtual environment that mirrors the physical energy community, integrating real-time data, predictive models, and optimization algorithms into a unified operational tool [402]. DTs allow managers to visualize and monitor energy flows, storage levels, and member interactions in real time, while also supporting predictive control and scenario analysis [403]. Tools such as Web-GIS platforms [377] contribute geospatial layers to the DT, enabling asset-level monitoring and spatially informed operational decisions. Systems like Emoncms [378] provide real-time data acquisition and analytics, ensuring that the DT remains synchronized with field conditions. Furthermore, frameworks such as EnergyCommunity.jl [379] integrate simulation and optimization engines directly into the

DT, enabling operators to test alternative dispatch strategies, evaluate demand-response participation, and assess the impact of new members or technologies before implementing changes in the physical REC.

By combining these computational techniques with DT infrastructures, REC management becomes more proactive, data-driven, and resilient [282]. It enables continuous adaptation to fluctuating renewable generation, dynamic user loads, and evolving market conditions while enhancing the community's economic and environmental performance [230,282].

Operational optimization

The operational optimization phase represents the stage in which RECs fine-tune their day-to-day functioning through data-driven strategies that enhance system performance. In the operational optimization phase, literature highlights a strong methodological focus on algorithmic implementations aimed at ensuring efficient, reliable, and cost-effective daily operation [240]. The most frequently used approach is linear programming [344], appearing in 20% of the reports. Within this category, the dominant algorithm is MILP [365]. These formulations are widely applied to optimize power flows, schedule distributed generation and storage assets [404], coordinate demand-response actions, and allocate energy among community members under economic, physical, and regulatory constraints [405,406]. Their ability to incorporate detailed system characteristics and multi-period decision structures makes them particularly well suited for operational tasks such as day-ahead and intra-day dispatch [163].

Alongside traditional linear programming, more dynamic control-oriented methodologies are gaining prominence. Model Predictive Control (MPC) [407], identified in 5% of reports, enables rolling-horizon optimization that continuously incorporates updated forecasts of renewable generation and load into short-term operational decisions [284,354]. This makes MPC particularly effective in managing uncertainty and variability, especially in communities with high shares of PVs, electric vehicles, or flexible loads [160]. Additionally, Agent-Based Modelling (ABM) [408] appears in 5% of reports as a powerful tool for representing the behaviours, interactions, and preferences of heterogeneous community members [409]. ABM enables the simulation of decentralized decision-making processes, cooperative and non-cooperative energy exchanges, and the emergence of collective operational patterns within the REC [410].

Together, these operational optimization approaches support highly granular and adaptive decision-making, forming a methodological backbone for efficient REC operation [290,411].

5. Discussion

The implementation of RECs requires a structured, multi-phase approach that integrates technical design, operational planning, management strategies, and continuous performance assessment. Although each phase offers multiple methodological options, literature clearly indicates which approaches are most frequently applied and have proven most effective.

Building on this understanding, the following section identifies the most suitable methodological approaches for each stage of REC development. By organizing these recommendations according to the REC lifecycle, it provides a comprehensive and actionable set of implementation guidelines to support the effective modelling, construction, and operation of RECs.

The phases of REC development are illustrated in Figure 3. It is particularly important to distinguish the sub-phases of the modelling and operational stages as the choice of methodological approach differs depending on the specific objectives within these phases.

Table 1 summarizes the recommended methodologies for each phase, providing the representative tools or algorithms, the type of approach, and the occurrence in the studies. Additionally, a complete tabulation of the frequencies for all identified methodologies is provided in Table S2 in the Supplementary Materials. The percentages shown here are the share of the specific methodological approach (X) within that REC phase as shown by Equation (1).

Table 1. Most commonly used and mature methodologies for each phase of development of REC.

Phase of REC	Type	Methodological Approach	Frequency
Pre-feasibility study	Algorithmic implementation	Unsupervised clustering	18%
Feasibility study	Comprehensive software program	Energy simulation software—EnergyPlus or TRNSYS more common	36%
REC design	Comprehensive software program	Energy simulation software—TRNSYS more common	44%
Refinement	Algorithmic implementation	Multi-Objective Optimization (MOO) algorithm	23%
Data gathering	Algorithmic implementation	Mixed-integer linear programming (MILP), numerical modelling or stochastic programming	5%
Management	Algorithmic implementation	Mixed-integer linear programming (MILP)	12%
Operational optimization	Algorithmic implementation	Mixed-integer linear programming (MILP)	11%

In the pre-feasibility study, unsupervised clustering has been largely researched [339] and is the most used methodological approach. This technique enables the identification of patterns and groupings in energy demand, consumption behaviour, or potential participant profiles, facilitating the initial assessment of REC viability. Its algorithmic nature allows for rapid processing of large and heterogeneous datasets. This provides researchers and REC developers with preliminary data-driven insights into optimal community composition, while offering policymakers and community stakeholders clear evidence of potential constraints and baseline viability [224]. However, this approach is sensitive to the quality and scaling of input data, since the optimal number of clusters can heavily depend on these factors.

Comprehensive software programs are repeatedly used in feasibility studies and REC design phases, where energy simulation environments such as EnergyPlus [359] or TRNSYS [67] are most common. These tools allow detailed modelling of energy flows, generation profiles, storage systems, and load interactions, providing quantitative support for investment and technology selection decisions [180,412]. Their status as comprehensive software programs makes them accessible to REC developers, researchers, and increasingly to community stakeholders who may not specialize in algorithmic implementations, thereby bridging the gap between technical analysis and practical decision-making [78]. Despite their comprehensiveness, these simulation tools require extensive, high-granularity input data, which are often difficult or expensive to obtain. Additionally, their computationally heavy nature makes them unsuitable for real-time operational control or iterative optimization, binding them primarily to the feasibility and design phases.

Indeed, the refinement phase marks the transition to algorithmic implementations, with Multi-Objective Optimization (MOO) [368] emerging as the primary approach. By simultaneously considering economic, technical, and environmental objectives, this method generates Pareto-optimal solutions that reflect the trade-offs inherent in REC modelling [42]. Such an approach enables decision-makers to select configurations that balance cost, energy efficiency, sustainability, and fairness among community members [144]. Nevertheless, MOO does not provide a single definitive answer; decision-makers are ultimately left

with the subjective task of selecting one final configuration from the resulting Pareto front. This can complicate the final consensus, especially when trying to balance the financial priorities of REC developers with the social and environmental expectations of community stakeholders.

Data gathering, management, and operational optimization currently represent the least researched phases in REC development, often lacking mature, comprehensive tools that are replicable and not context-specific. To bridge this gap and address the critical need for precise, data-driven control, algorithmic implementations dominate these stages. Techniques such as mixed-integer linear programming (MILP) [365], numerical modelling [371], and stochastic programming [372] are extensively employed to optimize dispatch schedules, manage storage and renewable generation, and accommodate uncertainties in load and generation profiles [140]. These approaches enable real-time decision-making and adaptive control, ensuring that REC operations align closely with predicted performance while responding dynamically to environmental and market fluctuations [298].

A significant limitation of these methods, particularly MILP, is their poor scalability, since computational time increases exponentially as the number of discrete variables grows, often requiring the oversimplification of non-linear real-world system dynamics. Similarly, stochastic programming relies heavily on the accurate estimation of probability distributions for uncertain parameters, which can be highly complex and data-intensive to formulate accurately, even for expert researchers. For software developers, bridging this gap by creating accessible interfaces for these complex algorithms remains a critical challenge, while policymakers must be aware of these technical limitations when designing regulations regarding real-time data reporting or grid compliance.

These findings also clarify that the three audiences addressed by the paper have different needs. For researchers, the main priority is to address algorithmic gaps through benchmark REC datasets, comparable validation procedures, and models that better integrate technical, social, behavioural, and regulatory variables. This would make it easier to determine whether optimization, forecasting, clustering, and control algorithms are transferable beyond individual case studies.

For REC developers, the key issue is tool maturity and scalability. Established tools such as EnergyPlus and TRNSYS, are relatively mature for feasibility assessment, simulation, resource mapping, and techno-economic analysis, but they are not always REC-specific. By contrast, REC-oriented monitoring platforms, energy-sharing tools, digital-twin prototypes, and optimization-based management systems are closer to operational REC needs, but often remain prototype-level or case-specific.

For policymakers, the main limitation is that many digital tools are not designed specifically for RECs and therefore do not explicitly include REC regulatory frameworks, administrative procedures, or compliance requirements. This reduces their usefulness for public authorities and municipalities who must translate regulation into practical implementation steps. A major need is therefore the development of clearer and more accessible user interfaces that can guide non-expert users through eligibility assessment, shared-energy monitoring, transparent benefit allocation, compliance reporting, and other regulatory tasks.

Overall, the table demonstrates a clear methodological progression throughout the REC lifecycle. In the early stages, simulation environments, clustering techniques, and scenario-based analyses play a crucial role in supporting strategic modelling and the preliminary configuration of community energy systems. These tools enable community stakeholders and policymakers to explore different design options, assess variability in consumption and generation patterns, and identify promising pathways before committing to more detailed analyses [89]. As the lifecycle advances, the methodological focus shifts

toward advanced algorithmic, optimization, and control-based approaches. These methods are essential for REC developers and grid operators managing day-to-day operations, coordinating distributed assets, supporting energy-sharing mechanisms, and enabling continuous system improvement based on real-time or high-resolution data [195].

The review highlights that current research converges toward a core set of recurring functions: energy simulation, techno-economic optimization, forecasting, and GIS-based resource assessment. Despite this, structural integration remains fundamentally weak. The majority of existing tools operate in silos, addressing isolated phases of the REC life cycle rather than providing a continuous link across modelling, construction, and operation. It is critical to note that similar barriers persist across all phases, specifically data availability, digital tools interoperability, limited user accessibility, and the inadequate integration of the social dimension—which frequently alienates community stakeholders. Together, these findings indicate that researchers and REC developers must move future REC tool development beyond fragmented solutions, prioritizing instead modular, holistic tools capable of seamlessly integrating all REC life cycle phases.

Taken together, these methodological patterns offer a structured view of how REC design and operation can be approached in practice. Rather than prescribing a single solution, the overview provides researchers, REC developers, policymakers, and community stakeholders with a set of well-established options that can be adapted to the specific objectives, regulatory contexts, and data environments of different communities.

By leveraging these guidelines, these distinct stakeholder groups can collaboratively outline a coherent and transparent framework for the development of RECs. Such a framework can help guide methodological decisions, support consistency across project stages, and encourage the deep integration of technical, economic, and environmental considerations.

Key Priorities and Challenges in RECs

Building on these insights from the literature, three key priorities emerge as the foundation for developing effective and scalable Renewable Energy Communities. These are: data interoperability [144], advanced modelling capabilities [156], and integrated digital tools [53]. Solving these would form a coherent technological pathway that supports robust system planning, operation, and long-term scalability in RECs.

The first priority is the development of high-quality, accessible, and interoperable data ecosystems. Reliable data is essential for feasibility assessments, model calibration, operational control, and long-term evaluation of RECs. However, current approaches are often constrained by fragmented, proprietary, or case-specific datasets [139,266,286,300,334,342,364], which hampers comparability across projects and limits the transferability of modelling tools. Establishing standardized protocols for collecting and sharing information on energy flows, techno-economic parameters [413,414], and environmental indicators would strengthen the consistency of REC analyses and support replicability at scale [128,415]. Ensuring interoperability between heterogeneous data systems is equally critical, particularly when integrating historical datasets with real-time measurements. Adopting open-data principles, along with privacy-preserving mechanisms, can further enhance transparency and trust while protecting sensitive user information [416].

On this data foundation, the second priority focuses on developing advanced modelling environments capable of supporting high-fidelity representations of REC behaviour [124]. Among these, DTs play an increasingly central role. DTs are dynamic, data-driven virtual replicas that continuously synchronize with the physical REC, enabling detailed simulations, predictive control, scenario analysis, and fault detection [402]. Their ability to link real-time data with optimized operation makes them a powerful tool for bridging the gap between planning and operational management. While their application

to RECs is still emerging, the growing interest in hybrid simulation-control approaches positions DTs as a key component in future REC development methodologies [88].

Building on advanced modelling capabilities, the third priority involves the creation of integrated digital tools that combine technical, economic, and environmental dimensions across the REC life cycle [71]. At present, most tools operate in isolation: optimization engines focus on operational control, while feasibility studies, economic analyses, and regulatory workflows are handled separately. Existing integrated frameworks [133,184,185,417] remain largely conceptual or prototype-level, with limitations in scalability, automation, and regulatory alignment. Furthermore, current digital tools do not yet fully support self-organized citizen groups in navigating the procedural and administrative requirements of REC development under the RED II directive [53]. A unified digital tool could streamline these processes by providing consistent system monitoring, transparent performance visualization, automated reporting, and decision-support features. Such an infrastructure would help reduce complexity while ensuring that modelling and operational tools remain accessible to a broad range of stakeholders [52].

These priorities have different implications for the main audiences addressed by this review. For researchers, interoperable datasets and advanced modelling environments would support more comparable and reproducible analyses, allowing algorithmic implementations and comprehensive software programs to be tested across common REC scenarios rather than isolated case studies. For REC developers, integrated digital tools represent a clear direction for future tool design, since they would allow single-function applications for simulation, forecasting, optimization, monitoring, and reporting to be connected into more scalable and user-oriented workflows. For policymakers and public authorities, these priorities highlight the importance of digital tools that can translate REC planning and regulations into practical procedures, supporting eligibility assessment, transparent benefit allocation, shared-energy monitoring, and compliance reporting under the European REC framework.

These key priorities outline a structured pathway for the next generation of RECs: grounded in interoperable data ecosystems, enhanced by advanced modelling and digital-twin capabilities, and supported by integrated digital tools that connect planning with operation. This framework provides a technological basis for improving REC scalability, robustness, and long-term performance.

6. Conclusions

This systematic review shows that methodological choices for RECs differ markedly across development phases. Technical stages (pre-feasibility, feasibility, design, refinement, data gathering, management, and operational optimization) are predominantly addressed through computational methods such as simulation, optimization, and quantitative modelling. In contrast, conceptual and qualitative approaches are primarily used during the stakeholder engagement phase. Comprehensive software programs are generally scarce, except during feasibility studies and REC design, where energy simulation tools such as TRNSYS and EnergyPlus are most frequently employed. Across the remaining phases, algorithmic methods dominate, with mixed-integer linear programming (MILP) emerging as the preferred approach.

Beyond these findings, the transition from isolated algorithms to integrated digital environments for REC planning and operation remains fundamentally incomplete. The current landscape is fragmented across three levels of maturity. First, comprehensive software programs are widely used but rarely REC-specific, frequently requiring expert users and complex, manual data preparation. Second, experimental REC-specific tools, such as energy-sharing platforms and digital twins, align better with developmental needs but

mostly remain unvalidated or highly case-specific prototypes. Finally, conceptual frameworks effectively structure participatory processes but often lack executable software and clear pathways for practical deployment, highlighting a critical gap between theoretical modelling and practical implementation.

From these patterns, three priorities emerge. First, establishing interoperable data ecosystems is fundamental: standardized, high-quality data are essential for comparability, replicability, and real-time operation. Second, advanced modelling environments can leverage these data to provide continuous, high-fidelity representations for forecasting, predictive control, and model validation. DTs represent a promising direction in this regard, although only a limited number of studies currently implement them for RECs. Third, integrating data and models into coherent digital tools will be necessary to link planning, operation, and monitoring processes and to reduce fragmentation across tools and stakeholders.

A key limitation of this review is its reliance on peer-reviewed literature, which may overlook practical tools, workflows, and decision-support systems used by municipalities, cooperatives, or private actors that are documented only in the grey literature or proprietary tools. The heterogeneity of national regulations, technical requirements, and REC definitions also complicates comparisons since methodological choices often depend on context-specific constraints and available data. Moreover, research attention is uneven across REC phases: early design stages are well covered, but operational management and long-term monitoring remain under-explored, limiting insight into mature, functioning communities. Finally, REC practices and digital tools are evolving rapidly, meaning that emerging approaches, such as Digital Twins and real-time monitoring architectures, may not yet be fully captured by the literature. Despite these limitations, the priorities identified in this review provide a coherent trajectory for future research and development, emphasizing the need to establish a robust data foundation, advance model-driven tools, and progressively unify capabilities through integrated digital tools to support scalable and resilient REC deployment.

From a review-process perspective, two additional limitations should be noted. First, although the screening and coding procedures were checked during manuscript development, the initial eligibility screening and data extraction were not performed independently by multiple reviewers. Second, a record-level list of excluded near-miss reports was not retained. These limitations should be considered when interpreting the completeness and reproducibility of the evidence map.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/en19163718/s1>, Table S1. Summary of methodologies, divided by phase, and frequency percentage across all reports reviewed; Table S2. Study-level grouping of reports included in the review.

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Abbreviations

The following abbreviations are used in this manuscript:

ABM	Agent-Based Modelling
AI	Artificial Intelligence
ANN	Artificial Neural Network
BESS	Battery Energy Storage System
CEC	Citizens Energy Community
CHDT	Cognitive Household Digital Twin
CO ₂	Carbon dioxide
DER	Distributed Energy Resources
DR	Demand Response
DSM	Demand Side Management
DT	Digital Twin
EMS	Energy Management System
EU	European Union
EV	Electric Vehicle
GHG	Greenhouse Gas
GIS	Geographic Information System
HVAC	Heating, Ventilation and Air Conditioning
IoT	Internet of Things
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LPWAN	Low-Power Wide Area Network
LPG	LoadProfileGenerator
MILP	Mixed Integer Linear Programming
MOO	Multi-Objective Optimization (MOO)
MPC	Model Predictive Control
P2P	Peer-to-Peer
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaic panels
REC	Renewable Energy Community
RED II	Renewable Energy Directive 2018/2001
RED III	Renewable Energy Directive 2023/2413
RL	Reinforcement Learning
SDG	Sustainable Development Goal
SME	Small and Medium Enterprise
UBEM	Urban Building Energy Modelling

Appendix A

Table A1. Summary of software utilized in the methodologies highlighted by this systematic literature review.

Reference	Software	Phase	Input	Output
[100]	Autodesk Forma (current cloud release; unversioned)	Feasibility study	Occupants behaviour, building characteristics, meteorological data	Local microclimate, energy retrofit
[418]	Balmorel 5.0	Feasibility study	Energy system, demand, generation	Cost-optimal dispatch, system analysis
[419,420]	BIFROST ZERO	Refinement, Operational optimization	Digital twin models, system parameters	Virtual testing results, system validation
[417]	Blumatica Impianti Solari 2.0	REC design	PV system parameters	PV electricity production, energy demand
[421]	CityBES (current web release; unversioned)	REC design	Urban building data	Energy performance simulation, retrofit analysis
[304]	CruISE platform (research platform; unversioned)	Refinement, Operational optimization	Mesh file of water surface	Body mass matrix, hydrostatic restoring matrix, offshore energy production
[422]	DECAPLAN (current platform release; unversioned)	REC design	PV systems, load data	Optimization of energy systems
[138,168]	Design Builder 2025.1	Feasibility study, REC design	Buildings characteristics	PV electricity production
[423]	Ecoinvent 3.12	Management	Life cycle datasets, energy system components, material inventories	Environmental impact indicators, emissions, LCA results
[198]	Emoncms 11.15.14	Data gathering	Time-series energy data	Visualizations, dashboards, analytics
[100,304]	Enea smart sim software 2.0	REC design	Meteorological data, building characteristics, electricity production, energy consumption and energy shared, plant system, occupants behaviour	Optimized consumption scenarios, energy needs, GHG emissions

Table A1. Cont.

Reference	Software	Phase	Input	Output
[424]	energy Atlas (current web release; unversioned)	Feasibility study	PV plant, REC geometry, meteorological data, buildings characteristics, energy consumption	KPIs, geothermal production
[38,199,425]	Energy Community.jl 0.3.1	REC design, Data gathering	Meteorological data, buildings characteristics, incentives, market data, renewable energy generation	REC scenarios, cost benefits, Net Present Value (NPV)
[140,327,403,426,427]	EnergyPLAN 17.0	Feasibility study, REC design, refinement, operational optimization	Energy system data, demand profiles, technology parameters, cost data	Energy system simulations, scenario analysis, cost—benefit results
[38,138,168,346,421,428]	Energy plus 26.1.0	Feasibility study, REC design, refinement	Meteorological data, buildings characteristics	PV electricity production, energy needs, HVAC scheduling
[417]	ENVI-met 5.9	Feasibility study	Urban morphology, vegetation data, surface materials, meteorological data	Microclimate simulations, thermal comfort indicators, environmental impact analysis
[235]	EureCa 1.0	REC design	3D building model, buildings characteristics	Energy consumption profiles
[175]	Flexmeter load profile generator (research tool; unversioned)	Pre-feasibility study	Appliance and user data	Load profiles
[198]	ForecastSolar (current web API; unversioned)	Pre-feasibility study	PV system data, meteorology	Forecasted PV production
[334,429]	GAIA Federated (research platform; unversioned)	Data gathering, management, operational optimization	Distributed data sources, user/asset profiles, energy measurements	Federated analytics, privacy-preserving predictions, community-level insights
[430]	GAMS 54.2.2	Operational optimization	Energy system parameters, demand, generation	Optimized energy dispatch, economic KPIs
[81,298]	Grafana 13.1	Management	CTM logic, time-series stored electricity	User interface to view energy consumption
[206]	GRASS GIS 8.5.0 software	REC design	GIS layers, meteorology, loads	Spatial analysis, energy potential mapping

Table A1. Cont.

Reference	Software	Phase	Input	Output
[185]	GSE Simulator (current web release; unversioned)	Management	PV system parameters, incentives	Energy production, economic KPIs
[188]	HAMS solver (current GitHub release; unversioned)	Refinemen	Mesh file of water surface	Body mass matrix, hydrostatic restoring matrix, offshore energy production
[78]	Gurobi software 13.0.2	Operational optimization	REC architecture, prosumers, PV electricity production, revenues, costs, incentives	Minimum operating cost of REC
[119,144,158,431]	HOMERPRO 3.18.2	Feasibility study, REC design	PV plant, REC geometry, meteorological data, buildings characteristics, energy consumption	REC scenarios simulations
[432]	IES-VE 2026	Feasibility study	Meteorological data, building characteristics, energy consumption, occupancy profiles	Energy class of buildings
[432]	IES-iVN (current platform release; unversioned)	Feasibility study	Meteorological data, building characteristics, energy consumption, occupancy profiles, energy class of buildings	Self-consumption index, Net Present Value (NPV)
[298]	InfluxDB 3.10	Management	CTM logic, time-series stored electricity	User interface to view energy consumption
[417]	i-Tree Eco 6	REC design	Tree inventory, site characteristics	Ecosystem service assessment, carbon storage
[142]	Ladybug 1.10.0 (Rhino plugin)	Refinemen	PV plant, REC geometry	PV electricity production, REC scenarios
[416]	LINDDUN GO (2024 edition)	Pre-feasibility, feasibility study	System architecture diagrams, data flows, user interactions	Privacy threat analysis, mitigation strategies, privacy risk reports

Table A1. Cont.

Reference	Software	Phase	Input	Output
[234,351,433]	Load Profile Generator (LPG) 10.10	Pre-feasibility, Feasibility study, REC design	Household characteristics, appliance data, occupancy patterns	High-resolution electric load profiles, behavioural demand simulations
[363]	Mapflow 3.0.0	Feasibility study	High-resolution ortho-image of the city	Potential surfaces for PV
[206]	Mosaik 3.6	REC design	Distributed energy system models	Simulation of grid and prosumers
[298]	Mosquitto 2.1.2	Management	CTM logic, time-series stored electricity	User interface to view energy consumption
[234]	oemof (Open Energy Modelling Framework) 0.6.4	REC design	Energy system parameters, demand, generation	Optimized dispatch, cost and energy flows
[31]	OpenDSS software 11.0.0.1	REC design	REC architecture, energy load, electricity production	Unbalanced power flow
[124]	OpenModelica 1.27.0	Feasibility study, REC design	REC architecture	Digital twin, virtual prototype
[434]	OpenSolar (current cloud release; unversioned)	Feasibility study	PV system characteristics	PV design, energy yield estimates
[283]	PARMENIDES (research platform; unversioned)	Operational optimization	Energy system and urban data	Simulation of energy scenarios
[224]	PlanHeat (QGIS plugin; unversioned)	Feasibility study	Geography of location	Heating, cooling, Domestic Hot Water (DHW) energy needs
[38,101,148,168,175,206,224,244,300,435–443]	PVGIS 6.0	Feasibility study	Meteorological data, buildings characteristics, PV plant architecture	PV electricity production, electricity consumption
[444,445]	PVsyst 8.1.0	Feasibility study, REC design, Refinement	PV system parameters, meteorological data, shading configuration	PV performance simulations, energy yield estimation, losses analysis
[443,446]	pyRES (current GitHub release; unversioned)	Feasibility study, REC design	Renewable resource data, technology parameters, demand profiles	Energy system simulations, renewable integration analysis, performance metrics

Table A1. Cont.

Reference	Software	Phase	Input	Output
[38,101,224,300,435–437]	PyQGIS 4.2.0 (QGIS plugin)	Feasibility study	Potential surfaces for PV, solar irradiation data	PV electricity production
[224,235,363,435,447]	QGIS 4.2.0	Feasibility study	Load profiles, meteorological data, census data of the members, GIS file	Geography of location (ortho-image), aggregation of consumers, energy needs, 3D building model
[185,243,438]	RECON (Renewable Energy Community ecONomic simulator) 2.2	Pre-feasibility, feasibility study, REC design, refinement	Members of REC, PV electricity production, energy consumption, building characteristics	Self-consumption index, energy self-sufficiency, GHG emissions
[436]	RECoupled (research tool; unversioned)	Feasibility study, REC design	Electricity production, energy consumption, battery storage	Battery schedule, REC self-sufficiency, REC configurations
[448]	Regenerative Electronic Loads (RELS; prototype; unversioned)	Pre-feasibility	Electrical load profiles	Load testing, system validation
[428]	Renewables.ninja (current web service; unversioned)	Feasibility study	Meteorological data	PV electricity production
[140,142]	Rhino 8.33.26188.13001	Feasibility study	Buildings characteristics	3D Building model
[434]	Rose Community Designer (current release; unversioned)	REC design	REC geometry, prosumer data	Optimized community layout, energy scenarios
[448]	SAPIENTE (research platform; unversioned)	Data gathering	REC data, building parameters	Decision support, optimization scenarios
[423,449]	SimaPro 10.5	Feasibility study	Life cycle inventories, material and energy flows, process models	Environmental impact assessment results, emissions, resource footprints
[263]	Simstock 0.3.1	REC design	Stock of appliances and energy systems	Load and consumption projections
[304]	SIMUL (research platform; unversioned)	Data gathering, operational optimization	Real data collected by sensors	REC behaviour

Table A1. Cont.

Reference	Software	Phase	Input	Output
[100]	S.I.R.E. Enea software (research tool; unversioned)	Refinemen	Energy demand, GHG emissions	Possible members, yearly average energy consumption, electricity production
[180]	SOLAR platform (research platform; unversioned)	Feasibility study	Community planner, community controller, home controller	REC schedule
[445]	Sunny Design 5.70	Feasibility study	PV system architecture, meteorological data, load profiles, module/inverter specifications	PV system performance, energy yield, system sizing, self-consumption indicators
[139,450]	System Advisor Model (SAM) 2025.4.16 Revision 2	Feasibility study	Potential PV surfaces, meteorological data, load profiles, financial parameters	PV electricity production, system performance, financial indicators, cost—benefit analysis
[298]	Telegraf 1.39.2	Management	CTM logic, time-series stored electricity	User interface to view energy consumption
[451]	Termolog 17	REC design	Building characteristics, occupancy, weather	Energy performance certificate, thermal demand
[141,181,203,256,412,447,452–455]	TRNSYS 18.05.0001	Feasibility study, REC design	PV plant, REC geometry, meteorological data, buildings characteristics, energy consumption	Energy performance of PV, heat pumps, hourly and average primary energy, GHG emissions, energy needs
[140,142,456]	umi (Rhino plugin; current Rhino 8 release; unversioned)	Feasibility study, REC design	Meteorological data, 3D building model, buildings characteristics, GIS, REC geometry	Hourly profiles of energy needs, annual energy consumption profiles, GHG emissions
[457,458]	WebGIS (web platform; no single version)	Data gathering	Action plan, objectives, GSE map	Energy proximity map, GIS

Table A2. Comparison matrix of comprehensive software and algorithmic implementations for RECs. ('X' indicates that the capability was explicitly documented in at least one reviewed report or directly associated with the tool/algorithm in its use within reviewed literature).

Tool/Algorithm	Simulation	Forecasting	Single-Opt.	Multi-Opt.	GIS Data	BEM	Economic Eval.	Open-Source	Decision Support
EnergyPlus	X					X		X	
TRNSYS	X					X			
OpenModelica	X							X	
DesignBuilder	X					X			
IES-iVN	X					X	X		
IES-VE	X					X	X		
Autodesk Forma	X					X			
ENEA Smart-Sim	X					X			
EnergyPLAN	X		X				X	X	
CruISE platform	X								
EnergyCommunity.jl			X				X	X	
RECON/RECoupled	X		X	X				X	
SOLAR platform	X							X	
Energy Atlas					X				
Rhino + umi	X			X	X				
Autocad/CAD software	X								
CityBES	X				X	X		X	X
Balmorel	X		X				X	X	X
BIFROST Virtual Testbed	X								
Blumatica Impianti Solari 2.0	X								
DECAPLAN	X						X		X
Ecoinvent 3							X		
Emoncms	X	X						X	
ENVI-met 5.6.1	X				X				
Eureca	X								X
Flexmeter		X							
ForecastSolar		X						X	
GAIA (federated)		X							
GAMS			X	X					
GRASS GIS					X			X	
GSE Simulator	X								
HAMS solver	X								
Homer Pro	X		X				X		

Table A2. Cont.

Tool/Algorithm	Simulation	Forecasting	Single-Opt.	Multi-Opt.	GIS Data	BEM	Economic Eval.	Open-Source	Decision Support
i-Tree Eco 6.0	X				X				X
PVGIS		X			X			X	
KNX (automation)									X
Load Profile Generator (LPG)		X						X	
Mosaik	X							X	
Multi-RCAT modem									
NEWA									
oemof	X		X	X			X	X	
OpenSolar	X								
PARMENIDES									X
PVsyst	X						X		
pymfm	X							X	
pyRES	X							X	
QGIS/PyQGIS					X			X	
RECON	X		X	X			X	X	X
Regenerative Electronic Loads (REL)	X								
Renewables.ninja		X						X	
Rose Community Designer	X				X				X
SAPIENTE	X						X		X
SimaPro 9.1	X						X		X
Simstock	X				X	X			
Simulink	X								
SIMUL-REC	X								
Sunny Design	X								
System Advisor Model (SAM)	X	X	X				X	X	
Termolog	X					X			
Web-GIS					X				
Forecasting Algorithms									
Random Forest Regression		X						X	
Neural Networks		X						X	
Stacked Bi-LSTM		X						X	
ARIMA/SARIMAX		X						X	
Linear Regression (MLR)		X						X	
Persistence Method		X						X	

Table A2. Cont.

Tool/Algorithm	Simulation	Forecasting	Single-Opt.	Multi-Opt.	GIS Data	BEM	Economic Eval.	Open-Source	Decision Support
GANs/DCWGAN		X						X	
Gradient Boosting Machine		X						X	
Machine Learning + AI (incl. RL, GANs)		X						X	
Extreme Gradient Boosting (XGBoost)		X						X	
Federated Learning (GAIA federated)		X							
ForecastSolar		X						X	
Non-Intrusive Load Monitoring (NILM)		X							
Unsupervised clustering		X							
Bayesian Optimization		X	X						
Optimization Algorithms									
Mixed Integer Linear Programming (MILP)			X	X			X	X	
Multi-objective Pareto Optimization				X			X	X	
Linear Programming			X				X	X	
Model Predictive Control (MPC)	X		X				X		
Brute Force Algorithm			X						
Ravine Method Algorithm			X				X		
Mixed-Integer Non-Linear Programming			X	X			X		
Genetic Algorithm			X	X					
Stochastic programming		X	X	X					
Monte Carlo simulation	X								
Convex optimization			X						
Generalized reduced gradient algorithm			X						
Conic projection			X						
Brute force tuning			X						
Peer-to-peer (P2P) trading algorithms			X						X
Aggregation algorithms			X						
Flex offer algorithm			X						

Table A2. Cont.

Tool/Algorithm	Simulation	Forecasting	Single-Opt.	Multi-Opt.	GIS Data	BEM	Economic Eval.	Open-Source	Decision Support
GIS/Spatial Analysis									
QGIS/PyQGIS					X			X	
ArcGIS Pro					X				
PVGIS		X			X			X	
Mapflow					X				
PlanHeat (QGIS plugin)					X				
WebGIS					X				
GRASS GIS					X			X	
CoDistFlow / iDistFlow			X	X				X	
Multi-Criteria Analysis									
SWOT Analysis									X
SCORE Approach									X
Multi-Criteria Decision Making (MCDM)									X
PANORAMA Tool									X
LEAP Model							X		X
Ecosystem Transition Unit (ETU)									X
PARMENIDES									X
Game theory			X						X

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