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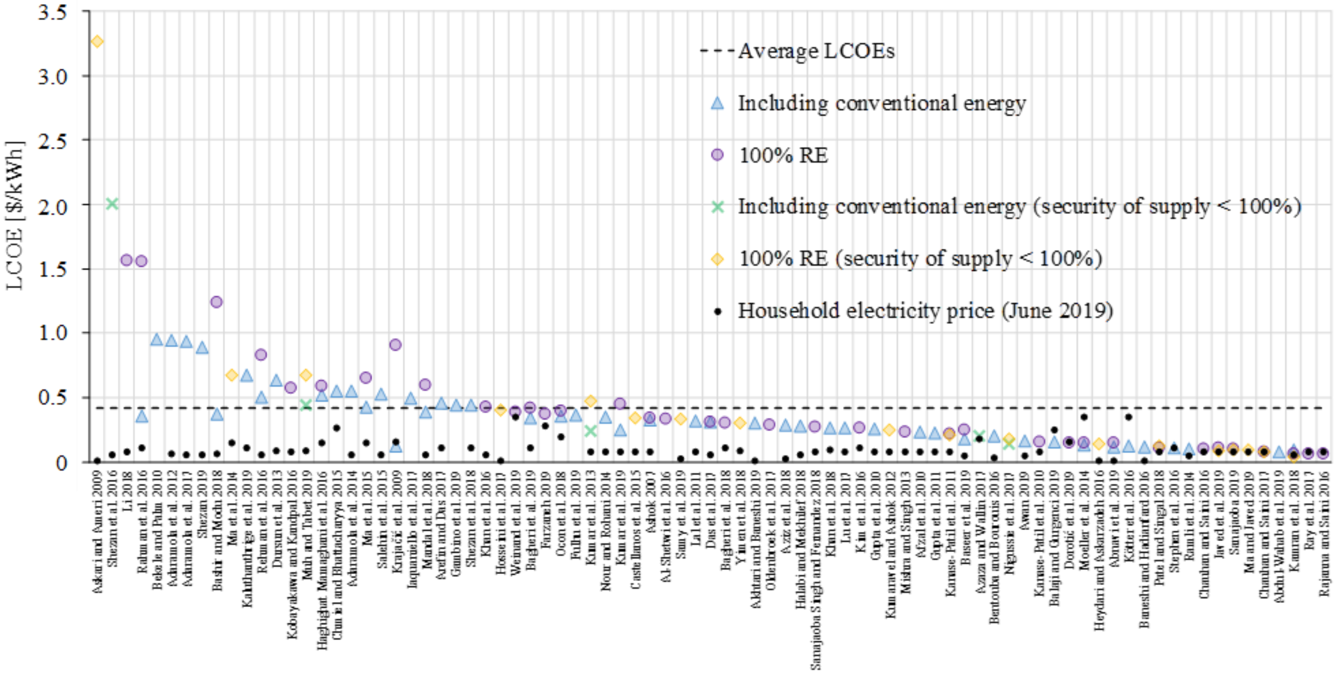

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Research attention on decentralized autonomous energy systems has increased exponentially in the past three decades, as demonstrated by the absolute number of publications and the share of these studies in the corpus of energy system modelling literature. This paper shows the status quo and future modelling needs for research on local autonomous energy systems. A total of 359 studies are roughly investigated, of which a subset of 123 in detail. The studies are assessed with respect to the characteristics of their methodology and applications, in order to derive common trends and insights. Most case studies apply to middle-income countries and only focus on the supply of electricity in the residential sector. Furthermore, many of the studies are comparable regarding objectives and applied methods. Local energy autonomy is associated with high costs, leading to levelized costs of electricity of 0.41 $/kWh on average. By analysing the studies, many improvements for future studies could be identified: the studies lack an analysis of the impact of autonomous energy systems on surrounding energy systems. In addition, the robust design of autonomous energy systems requires higher time resolutions and extreme conditions. Future research should also develop methodologies to consider local stakeholders and their preferences for energy systems.

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Abstract

Research attention on decentralized autonomous energy systems has increased exponentially in the past three decades, as demonstrated by the absolute number of publications and the share of these studies in the corpus of energy system modelling literature. This paper shows the status quo and future modelling needs for research on local autonomous energy systems. A total of 359 studies are roughly investigated, of which a subset of 123 in detail. The studies are assessed with respect to the characteristics of their methodology and applications, in order to derive common trends and insights. Most case studies apply to middle-income countries and only focus on the supply of electricity in the residential sector. Furthermore, many of the studies are comparable regarding objectives and applied methods. Local energy autonomy is associated with high costs, leading to levelized costs of electricity of 0.41 $/kWh on average. By analysing the studies, many improvements for future studies could be identified: the studies lack an analysis of the impact of autonomous energy systems on surrounding energy systems. In addition, the robust design of autonomous energy systems requires higher time resolutions and extreme conditions. Future research should also develop methodologies to consider local stakeholders and their preferences for energy systems.

Highlights

- Literature review includes 123 studies about local autonomous energy systems.
- Common trends in method, objectives, technologies and perspective
- Homer and EnergyPlan simulation models are most common
- Levelized costs of electricity for local energy autonomy are 0.41 $/kWh on average.
- Future work should focus on non-technical dimensions, open models and data

Keywords: Literature review, energy autonomy, off-grid systems, 100% renewable, energy system analysis, levelized cost of electricty, municipality, remote area

1. Introduction

Between 1993 and 2017, the percentage of the worldwide population with access to electricity increased from 77% to around 89% [1]. Since 2012, more than 100 million people per year have gained access to electricity. However, it is estimated that even in 2030 about 670 million people will still have no access to electricity [2]. Most people without access live in rural areas (84%) and in sub-Saharan Africa or developing Asia (95%) [3]. Negative examples include the developing countries of Burundi, Chad and Malawi, where less than 15% of the population have access to electricity [1]. Many of the newly electrified regions in developing countries apply off-grid solutions with diesel engines due to long distances to the national grid. Such completely energy autonomous systems are able to meet the energy demands of an entire community without energy imports [4].

Whereas these completely autonomous (i. e. off-grid) energy systems exist in developing countries mainly due to cost considerations, there are also efforts by municipalities and regions to become energy autonomous in industrialized countries with complete electrification (i.e. grid-connected). This is due to the energy transition and the related environmental awareness [5] as well as the desire of citizens to play an active role in energy supply and to be less dependent on central markets and structures (e. g. [6,7]). The majority of municipalities with energy autonomy aspirations strive for balanced energy autonomy and the focus is usually on electrical energy [5]. In this context, energy systems are balanced autonomous if they are energy neutral, i.e. the annual locally provided energy exceeds the annual demand [4]. In contrast to a completely energy autonomous solution, imports and exports are possible. In Germany, for example, municipal energy autonomy projects have increased exponentially since 1995 [8]. In 2017, 1,300 municipalities already participated in these projects, corresponding to 12% of all municipalities and 15% of the population in Germany [8].

Local energy autonomy can take different forms and degrees. In particular, autonomous energy systems need to exhibit the basic criteria as defined by Rae and Braedly [4]. First, the local system is able to generate at least as much energy to meet the demands. Second, the local system allows energy shifting possibilities for times in which there is a temporal mismatch between demand and supply (i.e. through storage or in the case of balanced autonomy through energy infrastructure). Third, the system is capable of operating independently on a *stand-alone* or *off-grid* basis. Thereby, local autonomy efforts are related to active participation of the community or rather the system components are owned by the community members. In general, autonomy efforts are directly related to the notion of *self-governance* and *community ownership* [4]. In this study, energy autonomy is defined the same way: it focusses on plants inside the municipality which tend to be operated by the local community, and may also include conventional technologies. However, due to the dependency on fuel transport and the high costs of diesel-based energy systems, a supply consisting at least in part of renewable energies could be worthwhile in these cases.

As the above examples demonstrate, balanced or completely autonomous energy systems are related to different objectives and have different effects on the local setting but possibly also on the overarching system. Due to the increasing relevance of local energy autonomy (c.f. section 3), there is a need to elaborate and define transition process aspects and successful transition pathways. Therefore, the aim of this study is to review the literature on *local* energy autonomy, i.e. in villages, districts, municipalities and regions, in order to identify the current state of the art and gaps or starting points for future studies. This spatial resolution is chosen since similar conditions apply, for example from a technical point of view (decentralised energy technologies) but also from a social point of view, such as the number and type of stakeholders. Studies on individual buildings and larger regions such as entire nations are therefore excluded. In contrast to the multitude of existing reviews, this paper for the first time shows a comprehensive overview and quantitative analysis of applied methods in energy autonomy case studies at the local level (cf. section 2).

This paper is structured as follows: section 2 gives an overview of already published literature reviews about energy system analyses with a focus on decentralized energy autonomy. Subsequently, section 3 presents the methodology for the literature search. Section 4 then presents and discusses the most important findings from the analysis of the literature, before the studies are critically assessed in section 5. A summary and conclusions are given in section 6.

2. Existing literature reviews

Some review papers have already examined studies on local energy system planning for larger (e.g. urban areas) [9,10] and smaller regions (e.g. municipalities / communities) [4,11–17]. In some cases, the focus is on some form of energy autonomy [4,11,16,17], or this topic is at least briefly discussed [12,15]. A few other review papers [18–21] discuss energy autonomy, but do not focus on the local level as defined in section 1. This section now gives an overview about these existing literature reviews.

Even though there are some undeniable differences regarding the motives of local energy autonomy efforts in developed and developing countries, due to the growing utilization of decentralized renewable-based energy generators local energy autonomy projects also represent a business opportunity in industrialized countries according to the review of Engelken et al. [22]. Despite all of the criticism voiced by Heard et al. [20], the feasibility and viability of such local renewable energy systems have been also demonstrated in various studies as shown in the reviews of Brown et al. [18] and Hansen et al. [19].

In this context, a strategy to achieve this feasibility requires the discussion of crucial factors regarding energy autonomy. Kaundinya and Ravindranath [17] present both general success and failure stories of corresponding autonomy projects. According to the authors, a generalized approach to assess the suitability of off-grid and grid-connected systems, based on techno-economic-financial-environmental feasibility does not find adequate coverage in the literature yet. A comprehensive balance between grid-connected and off-grid (i.e. completely autonomous) systems also requires higher and combined efforts from policy makers and modelling experts. Issues and trends shaping local energy systems are conceptually summarized by Keirstead et al. [9] and Koirala et al. [12]. Concerning this matter, local energy systems fit very well into the neo-liberal ideas of self-reliance and independence [12]. A shift towards local autonomous systems, however, is not only associated with a host of social, financial and environmental benefits. Key challenges are the degree and scale of energy autonomy, the matching of demand with supply, the importance of socio-economic and political factors and the structural requirements in remote communities [12].

These results go in line with the findings of the review of Rae and Bradley [4]. While taking into account the different drivers of balanced or completely autonomous energy projects, the review investigates environmental, political, economic, technical and social concerns. Even though generation and utilization of renewable energy is primarily a technical challenge, social and political aspects are the most important factors in its implementation in the community. The conceptual framework of energy autonomy by Müller et al. [16] shares a similar focus: the involvement and motivation of administrations and community stakeholders are decisive for the successful transition towards local energy autonomy. According to Rae and Bradley [4], future projects should rely on successful autonomy projects since they might provide valuable lessons of the impact of positive social engagement and community involvement. In this context, especially island and remote community projects have shown that a shift towards a more autonomous and sustainable energy system is achievable.

Additionally, ensuring stable supply and reliability against all plausible outcomes in renewable energy availability might raise cost and complexity of the systems due to the impacts of worst-case conditions [20]. Distributed energy generation as with local autonomous projects encompasses a wide variety of technologies which tend to be highly sensitive to the deployment context [15]. Thus, it is important to consider the necessary spatial and temporal boundaries of the region or community. This includes regional features but also limitation of regional resources not only with respect to wind or solar. In this context, Heard et al. [20] point out that special attention should be paid to the potential disruption to rivers and associated habitats from hydro-electricity as well as to the increasing dependency on biomass and associated reorganization of farming.

Some of the mentioned aspects have also been posed in terms of future modelling needs. Trans-disciplinary and multi-dimensional features of low-carbon community model approaches are outlined by Nakata et al. [21]: models should consider e.g. the utilization of waste for energy, the penetration of clean coal technologies, the inclusion of various sectors, and approaches related to energy-for-development issues in rural areas of developing countries. Dependent on the objectives and constraints, Gamarra and Guerrero [11] point out innovative planning guidelines by reviewing optimization techniques applied to microgrid planning. While the microgrid siting problem of autonomous systems requires robust methodologies, the operation of the autonomous system is only possible with reliable energy management systems. Thereby, stochastic optimization could be one solution for a more realistic estimate [17]. Furthermore, computer-based techno-economic assessment tools of grid-connected and off-grid systems should be combined with methods of material flow analysis or life cycle assessment [17]. Besides, Scheller and Bruckner [13] present requirements for energy system modelling at the municipal level and discuss existing optimization models concerning their fundamental approaches. Finally, they provide future modelling needs for successful energy system analyses which are also linked with the mentioned challenges of autonomy projects. Further general assessments of available methods and tools but also opportunities for future energy system planning at the community level are presented by Huang et al. [14] and Mirakyan and De Guio [10].

In contrast to many other literature reviews, the present paper presents a comprehensive overview and quantitative analysis of applied methods in case studies on energy autonomous systems at the local level. Of the reviews discussed in this section, only [4,11,12,15–17] focus on energy autonomy at the local level. Of these six papers, only Kaudinya et al. [17] and Gamarra et al. [11] concentrate on methodological aspects. However, the studies differ from the present review study by concentrating on the comparison of grid-connected and off-grid energy systems [17] or only on microgrid studies [11]. Furthermore, the studies are from 2009 [17] and 2015 [11], respectively, and since then, the published articles on local energy autonomy have more than doubled (cf. section 3). Apart from the general topic, this review also covers new aspects such as a compilation of costs for local energy autonomous systems (cf. section 4.7).

3. Review methodology

The literature on local energy system analysis has increased exponentially from 1990 until 2019 (cf. Figure 1), along with the local energy autonomy efforts described in section 1. Scopus[1] was used for the primary literature search, since it covers a wider range of journals [23] as well as more recent sources [24] than other databases like *Web of Science*. The initial search query in Table 1 results in a total of 2,453 studies (cf. bright part of the search query and bright curve in Figure 1). The search query contains the methodology (e. g. energy system analysis or simulation), the spatial resolution (e. g. municipality or region) and the restriction that it is a peer-reviewed article. 359 (15%) of the 2,453 studies on local energy system analyses deal with autonomous energy systems and have also exponentially increased in recent years (*Adjusted search* in Table 1 and dark part of search query and diagram in Figure 1).

Table 1: Different search queries for the literature search in Scopus. Included are publications, which were published between 1990 and 2019.

Search name	**Search query**	**Number of studies**
Initial search	TITLE-ABS-KEY ("energy system" AND ("simulation" OR "modelling" OR "optimisation" OR "analysis") AND ("region" OR "municipalities" OR "municipality" OR "communities" OR "community" OR ("district" AND NOT "district heating") OR "city" OR "cities" OR "town" OR "remote")) AND (LIMIT-TO (DOCTYPE,"ar"))	2,453
Adjusted search	TITLE-ABS-KEY ("energy system" AND ("simulation" OR "modelling" OR "optimisation" OR "analysis") AND ("region" OR "municipalities" OR "municipality" OR "communities" OR "community" OR ("district" AND NOT "district heating") OR "city" OR "cities" OR "town" OR "remote") AND ("off-grid" OR "off grid" OR ("100%" AND "RE") OR ("100%" AND "renewable") OR "100%-renewable" OR ("energy" AND "autonomy") OR ("energy" AND "autarky") OR ("energy" AND "self-sufficiency") OR ("energy" AND "self-sufficient") OR "energy independent" OR "stand-alone" OR "energy autonomous" OR "island system")) AND (LIMIT-TO (DOCTYPE,"ar"))	359
"Energy system analysis" search	TITLE-ABS-KEY("energy system" AND ("simulation" OR "modelling" OR "optimisation" OR "analysis")) AND (LIMIT-TO(DOCTYPE,"ar"))	12,368

The increasing importance of the topics could be only related to the generally exponentially increasing number of publications. However, the share of local energy system analyses in the field of energy system analysis (*Energy system analysis search* in Table 1) has increased from 8% (1990) to 20% (2019) and that of local energy autonomous systems from 0% to 3%.

The 359 studies about local energy autonomy were examined for suitability for this review. 236 studies were excluded for the reasons outlined in Table 2. For 122, most of them were excluded because of an unsuitable spatial resolution (e.g. energy system analysis of a single building). A total of 123 studies remained ([8,25–146]), which were mainly published in the journals Energy and Renewable Energy (cf. Table 3). In addition, Table 4 shows the ten most globally cited articles on local energy autonomy.

[1] https://www.scopus.com/search/form.uri?display=basic

Table 2: Studies that resulted from the adjusted search in Scopus and are not considered in this literature review for the reasons given in the table.

Exclusion criterium	**Number of studies**	**References**
The study does not consider energy autonomy as defined in section 1 (i. e. at least balanced autonomy has to be analysed)	30	[147–176]
Autonomy is considered in a different context than energy	2	[177,178]
Autonomy is only mentioned as a future target in the paper	3	[179–181]
The spatial resolution of the study does not match our definition of local energy systems (cf. section 1)	**122**	
• Single consumer / households / building	41	[182–222]
• Single commercial application	**57**	
○ Agricultural well	2	[223,224]
○ Desalination unit	7	[225–231]
○ Cellular base station / telecommunication unit	11	[232–242]
○ Hospital / healthcare facility	5	[243–247]
○ Hotel	5	[248–252]
○ Library	1	[253]
○ Wireless sensor nodes	1	[254]
○ Machinery laboratory	1	[255]
○ Agricultural application (farm or irrigation area)	6	[256–261]
○ Voter registration centre	1	[262]
○ Desert safari camp	1	[263]
○ Touristic facility	1	[264]
○ Charging station	1	[265]
○ Mining site	3	[266–268]
○ Factory / enterprise	3	[269–271]
○ Refinery	1	[272]
○ Road lighting system	1	[273]
○ University facility / school	4	[274–277]
○ Clean water and toilet system	1	[278]
○ Wastewater treatment plant	1	[279]
• Large regions	3	[280–282]
• One or several countries	21	[283–303]
Analysis of a single energy plant / technology	35	[304–338]
Aerospace applications	2	[339,340]
Climate analyses	4	[341–344]
Study focusses on control strategies of an energy system	13	[345–357]
Study introduces a new model without autonomy case study	3	[358–360]
Study develops load profiles for off-grid areas	2	[361,362]
Study focusses on qualitative analysis	15	[363–377]
Analysis of a given 100 % renewable system	2	[378,379]
Text language: Korean	2	[380,381]
Publication not found	1	[382]

Table 3: Distribution of the studies among the journals in which they were published. Only those journals are shown which have published five or more studies.

Journal	**Number of studies**	**Share in 123 studies [%]**
Energy	16	13
Renewable Energy	14	12
Energy Conversion and Management	9	7
International Journal of Renewable Energy Research	9	7
Applied Energy	7	6
Energies	7	6
Journal of Cleaner Production	6	5
Solar Energy	5	4

Table 4: Most relevant articles on local energy autonomy, based on global citations (15.01.2020).

Article	Title	Journal	Global citations
Ashok 2007 [34]	Optimised model for community-based hybrid energy system.	Renewable Energy	295
Ma et al. 2014 [134]	A feasibility study of a stand-alone hybrid solar-wind-battery system for a remote island.	Applied Energy	257
Kanase-Patil et al. 2010 [73]	Integrated renewable energy systems for off grid rural electrification of remote area.	Renewable Energy	187
Østergaard and Lund 2011 [101]	A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating.	Applied Energy	180
Ma et al. 2014 [86]	Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong.	Renewable Energy	158
Maleki and Askarzadeh 2014 [89]	Optimal sizing of a PV/wind/diesel system with battery storage for electrification to an off-grid remote region: A case study of Rafsanjan, Iran.	Sustainable Energy Technologies and Assessments	102
Haghighat Mamaghani et al. 2016 [61]	Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia.	Renewable Energy	95
Gupta et al. 2010 [59]	Steady-state modelling of hybrid energy system for off grid electrification of cluster of villages.	Renewable Energy	92
Rohani and Nour 2014 [112]	Techno-economical analysis of stand-alone hybrid renewable power system for Ras Musherib in United Arab Emirates.	Energy	89
Askarzadeh and dos Santos Coelho 2015 [37]	A novel framework for optimization of a grid independent hybrid renewable energy system: A case study of Iran.	Solar Energy	85

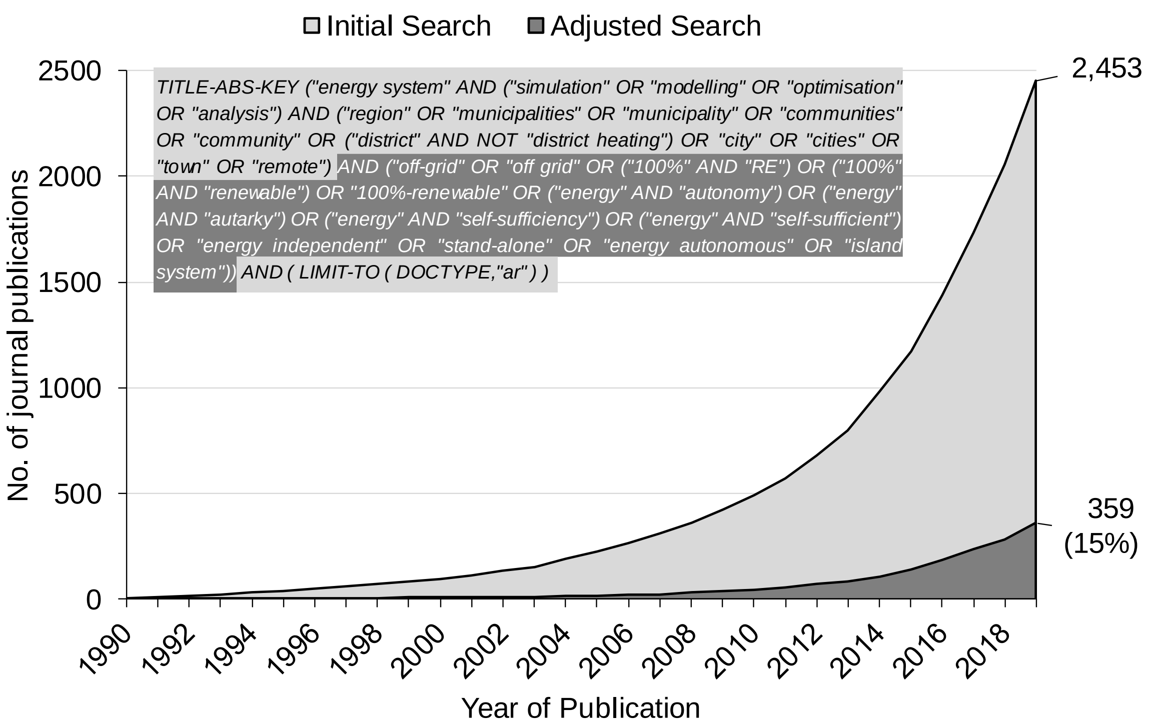

Figure 1: Development of the number of journal publications for two search queries in Scopus. The bright curve contains the publications on energy system analyses at the local level. For the dark curve, the search query has been adjusted so that the studies also deal with autonomous energy systems. The last search in Scopus was performed on November 20, 2019.

4. Results of the literature review

This section presents and discusses the main findings of the analysis of the 123 studies. First, section 4.1 explains the methods and models used in the studies. Subsequently, section 4.2 shows the system boundaries, i.e. which spatial resolution and which types of demand and consumption sectors are considered. The type and feasibility of energy autonomy under consideration is presented in section 4.3. In the following section 4.4, the temporal resolution is discussed. Section 4.5 then indicates the included technologies before section 4.6 examines the consideration of grid infrastructures. Finally, section 4.7 compares and discusses the costs for local energy autonomy resulting in the studies.

The supplementary Microsoft Excel file in the online appendix contains all the information discussed in this article. Not all aspects could be identified in all studies. In some of these cases, the information in the online table are given in parentheses, which indicates assumptions based on detailed analysis of the study. If, in the following sections, the shares in the number of studies do not add up to 123 or the percentages do not add up to 100%, this is due to the fact that not all information could be retrieved from every study.

4.1. Methodologies and models

The methods employed in the reviewed literature (cf. Table 5) range from simple energy balancing calculations (e. g. [71,100,105]) to simulations (e. g. [80,95,103]), metaheuristics (e. g. genetic algorithm [70], discrete harmony search [89], artificial bee swarm optimization [90,91] or flower pollination algorithm [114]), mixed-integer linear optimizations (e. g. [31]) and multi-objective optimizations (e. g. [113]).

Table 5: Overview of the general methodologies applied in the studies.

General methods	Study	Number of studies
Artificial bee swarm optimization	[90,91]	2
Biography based optimization algorithm	[133]	1
Chaotic search	[128,129]	2
Cukoo search	[116]	1
Discrete harmony search	[48,89,128]	3
Electricity System Cascading Analysis	[65]	1
Energy balancing calculation	[71,100,105,123]	4
Firefly algorithm	[115]	1
Flower Pollination algorithm	[114]	1
Fuzzy analytic hierarchy process	[99]	1
Genetic algorithm	[70,107]	2
Grey relation analysis	[99]	1
Life cycle cost analysis	[88]	1
Multi-objective particle swarm optimization	[38,125,126]	3
Multi-objective crow search algorithm	[69]	1
Multi-objective optimization	[113]	1
Non-dominated sorting genetic algorithm-II	[125,126]	2
Optimization	[8,31,35,50,55,57,59,60,64,73,75,79,93,99,110,118,146]	16
Multi-criteria-decision analysis (MCDA)	[81,93]	2
Particle swarm optimization	[37,62,102]	3
Simulated annealing	[128]	1
Simulation	[25–30,32–34,36,39–44,46,47,49,51–54,56,58,61,63,66–68,72,76–78,80–87,92,94–98,101,103,104,106,108,109,111,112,117,119–122,124,127,130–132,134–145]	69

When investigating the methods, it is striking that in most cases only simplified calculations are carried out. For example, the number and size of plants is usually predefined and not optimized. Simulations are frequently used (56%, cf. Table 5) and often referred to as optimization. The best examples are the simulation softwares HOMER and EnergyPLAN, which are used in 61 (50%) and 7 (6%) studies respectively (cf. Table 6). Apart from HOMER and EnergyPLAN, other models appear only once or twice or are not specified in the studies (cf. Table 6).

Although most HOMER studies call it optimization, in its core HOMER is a simulation model [383]. First, plant types and capacities as well as load demand profiles and renewable potentials are specified. Then the simulation is used to balance energy generation and consumption and calculate the costs. Thousands of scenarios with different parameters can be simulated in a sensitivity analysis. Subsequently, in the so-called optimization, the best solution is selected from among all scenarios depending on the selected criterion (e.g. minimization of costs or fuel usage) [383]. This explorative approach to identifying a pareto front does not necessarily yield the optimal solution. The vast majority of the studies reviewed here in which HOMER is used have a similar structure: First, the economic parameters, the load profile as well as the renewable potentials and the energy system under consideration are described for a particular application. The best energy system is then usually selected on the basis of costs (97% of cases). These studies therefore typically focus on case studies rather than methodological innovations. The aim of these studies is usually to reduce the diesel consumption of a remote off-grid area. In three studies, newly developed methods were compared with the HOMER model. The results showed that a Biogeography Based Optimization (BBO) algorithm [133], a Genetic Algorithm [70] or the so-called LINGO model [73] perform better than the HOMER model in terms of computing time and minimization of costs. The BBO algroithm, for example, found a better solution than HOMER and reduced the computing time from 15 h to 0.7 h [133].

Table 6: Models used in the analysed literature.

Model	Study	Number of studies
HOMER or HOMER Pro	[25–30,33,36,39,40,42–44,46,47,49,51,54,56,58,61,63,66,67,72,76–78,81–84,87,92,94,96–98,106,108,109,111,112,119–122,127,131,132,134–142,144,145]	61
EnergyPLAN	[45,52,53,101,117,124,130]	7
RE³ASON	[8,93]	2
BeWhere / Phasma	[118]	1
FINE / TSAM	[146]	1
FlexiGIS	[31]	1
H_2RES	[80]	1
IREOM	[74]	1
ISLA	[99]	1
LINGO v.10	[73]	1
OSeMOSYS	[57]	1
P²IONEER	[79]	1
RegFin	[105]	1

Despite the weaknesses that HOMER shows in determining an optimal energy system, the advantages of the tool should also be appreciated. It is an open access tool that can be used by everyone and does not require a lot of computing power. Therefore, the model is particularly useful for studies on remote areas in countries with low or middle income (75% of the HOMER studies reviewed here) according to the country classification of the World Bank [384] (cf. Table 8).

In contrast to the HOMER model, the EnergyPLAN model was only used for case studies in countries with middle (China [130]) or high (Italy [45], Croatia [52,117], Denmark [53,101], Ireland [124]) income. However, this model is also classified "as a simulation tool rather than an optimisation tool" [385] and only includes a dispatch optimisation. This means that the user has to specify the technologies and thus has to have a comprehensive understanding of energy system analysis (as in HOMER). A step in the right direction was the introduction of Homer Pro, which is intended to simplify the use of the HOMER software for inexperienced users [386].

Beyond these two models, there are more and more model approaches that generate inputs for optimization models on the basis of publicly available data such as OpenStreetMap[2]. Examples in the reviewed literature are the FlexiGIS model [31] and the RE³ASON model [8,93]. At least for FlexiGIS an open-source publication in GitHub is planned, according to the authors [31]. These models would enable inexperienced users in the field of energy system analysis to determine the energy potentials of a region and optimize the energy system. Neither potentials nor technologies and plant sizes would have to be determined before application of the models.

4.1.1. Perspective

In most energy system analyses, a *central planner* was used as the perspective. Only in Ramchandran et al. [108], the perspective of a Renewable Energy Service Company was taken instead. On the one hand, these central planner approaches show the macroeconomic optimum. On the other hand, however, these approaches often fall short of realisation: it could be difficult to convince individual homeowners to install the technologies in their homes that are optimal from a macroeconomic but not a business point of view. Therefore, studies of possible incentive systems that could encourage homeowners to implement the macroeconomic energy autonomy plan are required. First conclusions could be drawn by comparing the optimal energy system at building level from the perspective of the building owner on the one hand and from the macroeconomic perspective on the other.

Promising approaches include for example the combination of optimization approaches with *multi-criteria-decision analysis* (MCDA), as in [81] and [93]. These types of analyses do not yet include the perspective of every inhabitant, but at least the perspective of their most important representatives. This could help to strengthen the feasibility of an energy autonomy plan.

4.1.2. Target criterion

The adopted perspective is closely linked to a further shortcoming of many of the studies examined: the choice of the target criterion. In 103 (84%) of the studies only costs were minimized. As already shown in section 1, however, costs are not the only reason for energy autonomy projects. In a few studies, a different target criterion than costs is applied, but these analyses do not represent an improvement since also only one criterion is considered: technical feasibility [86,117], annual efficiency [103,104] or coal consumption [130]. However, beside the above-mentioned

[2] https://www.openstreetmap.org/

MCDA approaches, other multi-objective approaches represent improvements. In addition to costs, the criteria in Table 7 are also taken into account in the reviewed studies. Possible weightings for the criteria could either be determined on site before the case studies, or taken from surveys such as in [5].

Table 7: Applied target criteria besides cost in the studies with MCDA or multi-objective optimizations.

Criterion	**Study**	**Number of studies**
CO_2 emissions	[71,81,93,99,113]	5
Land use	[55,71,81,84]	4
Security of supply	[38,69,84,99]	4
Forecast accuracy	[125,126]	2
Renewable share in energy supply	[38,84]	2
Social acceptance	[81,99]	2
Community net imports	[93]	1
Creation of jobs	[81]	1
Ease of installation and operation	[99]	1
Flexibility of the system for future expansion	[99]	1
Gross domestic production	[105]	1
Health issues	[81]	1
Human development index	[81]	1
Noise	[81]	1
Risk of flash floods	[81]	1
Technical efficiency	[81]	1
Technical reliability	[81]	1
Technical lifespan	[81]	1
Technical scalability	[81]	1
Technical maturity	[81]	1
Universal education and gender equality	[81]	1
Water consumption	[55]	1
Water quality	[81]	1

4.2. System boundaries

This section first persents the spatial resolution and location of the case studies in the reviewed literature (cf. section 4.2.1). Section 4.2.2 then shows that the focus is primarily on the demand product electricity. Finally, the demand sectors considered in the studies are highlighted (cf. section 4.2.3).

4.2.1. Spatial resolution and location

Table 8 classifies the case studies of the reviewed papers according to the income classification of *The World Bank* [384]. Most of the studies were conducted in the *lower middle income country* (LMIC) India (21), *upper middle income countries* (UMIC) Iran (17) and China (6) as well as the *high income country* (HIC) Germany (7). Whilst the case studies in India and Iran focused mainly on the energy systems of remote areas without grid connection, in Germany a complete electrification already exists. The case studies on complete autonomous energy systems in high income countries are therefore more about isolating communities from the transmission grid. These studies are linked to the question whether the energy system transformation should be achieved through decentralised or centralised expansion of renewable energy sources. In [387], for example, the decentralised expansion is evaluated as more cost-effective for the German case due to higher required transmission grid expansion costs in the centralised case. The possible impacts of autonomous communities on the surrounding energy system (cf. section 4.3) therefore plays a very important role especially in the HIC studies.

Whilst the *low income countries* (LIC), the LMIC and the UMIC mainly consider remote rural areas as case studies with 100%, 92% and 74% of the studies, respectively, these remote areas account for only 23% of the studies on HIC. Instead, studies on HIC also often investigate energy autonomy for islands (23%), cities (20%), regions (17%) and municipalities (14%). This is also reflected by the number of residents examined in the case studies: in the studies on LIC, LMIC and UMIC case studies with a maximum of 4,750 inhabitants are analysed; in the HIC studies, case studies with up to 640,000 inhabitants are investigated. The exact area or city names of the case studies as well as the number of households and inhabitants examined can be found in the supplementary Excel file.

In this context, it is noticeable that the complexity of the applied methodology adapts to the size of the considered region. This means, the smaller a region is chosen, the more details can be included in the analysis. For example, in Waenn et al. [124] the operation of the energy system with 640,000 inhabitants is determined with the help of a less complex simulation (EnergyPLAN). The largest case study in which an energy system is designed with the help of an optimization is in Schmidt et al. [118]: a large region with 21,000 inhabitants. However, in Schmidt et al. only two time slices are considered during the optimization (cf. section 4.4.2) to reduce the model complexity.

In [8,61,77,105,107,112,144] different spatial scales were compared as case studies, i.e. the number of households or inhabitants was varied. However, these studies do not yet provide indications about the optimal size of energy autonomous energy systems.

Table 8: Classification of the countries according to The World Bank [384], in which the case studies are conducted in the reviewed literature as well as the share in the total of 123 publications. This country classification is based on the gross national income per capita [387].

Income group [384]	Gross national income per capita [384] [$]	Countries and studies	Share [%]
Low income	[0; 1,025)	Ethiopia [67,97], Rwanda [144], Tanzania [140], Yemen [32]	4
Lower middle income	(1,025; 3,995]	Bangladesh [51,92,136], Cameroon [96,127], Egypt [114], Ghana [27,29], India [30,34,46–48,59,60,73,74,78,82,88,94,102,107,108,110,115,116,131,133], Indonesia [33,121], Nigeria [28,137,139], Pakistan [72,76,111], Philippines [99], Timor-Leste [57]	33
Upper middle income	(3,995; 12,375]	Algeria [44,135], Brazil [119], China [70,81,83–85,130], Colombia [61], Cuba [132], Iran [26,35–37,42,62,64,66,69,89–91,125,126,128,129,141], Iraq [138], Malaysia [63,65,120,122], Maldives [56], Mexico [55], Turkey [54]	30
High income	(12,375; inf)	Australia [41,58], Austria [118], Canada [39,40,106,123,145], Croatia [52,80,117], Denmark [53,101], Finland [105], Germany [8,31,71,79,93,95,146], Greece [103,104], Hong Kong [86,87,134], Ireland [124], Italy [45], Japan [143], Korea [77], Oman [25], Saudi Arabia [43,109,142], Scotland [49], Sweden [38], Switzerland [113], United Arab Emirates [98,112], USA (Alaska) [50]	33

4.2.2. Demand

In all the studies reviewed, the electricity demand of the energy system is included. Heating or cooling demand, on the other hand, is only considered in 30 (24%) or 13 (11%) of the studies, respectively. As already indicated in section 1 for energy autonomy projects, this also demonstrates the focus on electricity in the literature. In most cases, the demand is based on time series that have been determined or collected beforehand. However, there are also examples of energy autonomy case studies such as [8,31,93], in which the demand and load profiles are determined automatically on the basis of publicly available data. The electricity and heat generation technologies used in the studies are presented in section 4.5.

In addition to electricity and heat, other demand products such as food are also indirectly taken into account, for example through land-use competition as in Schmidt et al. [118]. However, only direct demand products are discussed in the present literature review. This includes the demand for water considered in ten studies. In [29,47,48,64,94] this is considered by the electricity demand of a water pump, e. g. for an agricultural well. In [68,75,80,90] the energy system contains a desalination unit for water distillation. In Fuentes-Cortés et al. [55] the *water-energy nexus* is considered in the analysis, which means that water demand in the energy supply is taken into account. In this case the water demand includes fresh water for households, water used for regulating the temperature of the thermal demand as well as water needed as by-product in the combined heat-and-power (CHP) units. Water consumption is included in [55] alongside costs and land use in the multi-objective function of the optimization model. Therefore, [55] in particular shows a suitable way to consider water demand in future studies about autonomy. The studies [48,55,75,80] are the only examples which consider all three types of demand (electricity, heat and water).

4.2.3. Consumption sectors

Among the consumption sectors, mainly the residential sector is considered (102 studies; 83%), followed by the commercial sector (55; 45%), industrial sector (23; 19%) and transportation sector (11; 9%). The energy system is usually designed for all considered sectors. By contrast, in Bagheri et al. [39] the residential, commercial and industrial sectors are examined in separate analyses. Thereby, the energy system for the industrial sector shows the lowest *levelized cost of electricity* (LCOE) in the autonomous case with 100% renewable energies. Whilst the commercial sector with schools and hospitals also is important in studies about remote areas, larger industries and the transport sector are considered almost exclusively in case studies for municipalities, cities, islands or larger regions. In [73,74], industries are also considered in remote villages. However, they are referred to as *rural industries*, which probably corresponds more to the commercial sector of HIC in terms of demand structure. An interesting point is that in the cases where heat and industry were regarded, only a balanced autonomy is part of the analysis. This is probably due to the fact that, for example, high-temperature heat in industry can only be generated with specific renewable energy plants and, in the completely autonomous case, would be associated with excessively high costs.

For residential, commercial and industrial sectors, the demand is usually known in advance in the studies. However, for the consideration of the transport sector several different approaches are applied. In [71,101,105,124] a fixed fuel demand for traditional vehicles is covered. In [52,53,117], electric vehicles (EVs) are considered within the EnergyPLAN model. In Dorotić et al. [52] all vehicles and ferries on the island of Korčula in Croatia are replaced by electrically powered alternatives. The EVs not only serve as batteries, but can also be used for vehicle-to-grid, i.e. feeding electricity from the EV battery into the grid. Šare et al. [117] analyse three scenarios for the municipality Dubrovnik in Croatia with different EV penetrations in 2020, 2030 and 2050. Krajačić et al. [80] and Oldenbroek et al. [100], on the other hand, included fuel cell vehicles in their energy system analyses. In some scenarios in [80] the transport load is covered 100% by renewable hydrogen. None of the studies optimizes the number of electric or fuel cell vehicles.

4.3. Feasibility and type of autonomy

In the reviewed literature, studies on completely autonomous energy systems predominate with 110 (89%), whereas balanced local energy autonomy is only considered in 14 (11%) studies. The only study that analyses both cases seems to be Sameti and Haghighat [113], in which a net-zero energy district is investigated in three scenarios with grid connection and one as a stand-alone variant without grid connection.

Generally energy autonomy is feasible in the case studies. The only exception is the study by Alhamwi et al. [31] who do not obtain a feasible solution in their energy system model and come to the conclusion that an off-grid city (165,000 inhabitants) is economically and technically not practicable. However, there are also other examples which do not come to a favourable result for local energy autonomy. Krajačić et al. [80] find that the cost of electricity for a *100% renewable island* is up to 15 times higher than the current (2009) electricity price. Furthermore, in Oldenbroek et al. [100] a 100% renewable supply can only be achieved if 20% of the vehicle fleet are fuel cell vehicles. Also Šare et al. [117] come to the conclusion that large storage capacities are necessary for a 100% renewable supply. Jenssen et al. [71] show that the available biomass potentials of a model municipality are sufficient for 100% power and heat supply, but not to replace transport fuel. All these examples have in common that they examine bigger regions, cities and islands as case studies in high-income countries in Europe.

In the studies on completely autonomous energy systems, uncertainties due to disconnection from the grid infrastructures should play a very important role, since a non-optimal design of the energy system cannot be compensated by imports. Therefore it is even more important to design these energy systems robustly. There are several appropriate approaches in the studies. For example, in 39 (32%) studies a possible security of supply below 100% is implemented as a *loss of power supply probability* (LPSP). In most cases ([35–37,46,48,59,60,64,66,70,72–74,82,83,85,86,90–92,96–98,102,110,114,115,127,129]), the LPSP is modelled as a fixed value or results from other fixed values. Other studies ([38,62,69,84,99,107,116]) in which the LPSP is associated with weightings or penalty costs and thus integrated into the objective function of an optimization represent an improvement. In Hakimi et al. [62] different penalty costs were assumed for the residential, commercial and industrial sector. In future studies, the so-called *value of loss load* could be a suitable estimation of penalty costs. In Shivakumar et al. [388], for example, the value of loss load was calculated for households in all European Union member states. This data set with penalty costs based on the same methodology could make results of studies more comparable. As expected, the LPSP are rarely considered in high income countries, as the inhabitants are accustomed to high security of supply. Four case studies in Canada [145], Sweden [38] and Hong Kong [86,134] are the only examples. However, for autonomous systems these LPSP become more relevant.

Further studies try to robustly design off-grid energy systems by taking extreme conditions into account. In Petrakopoulou et al. [103,104], the plants of the energy system are over-dimensioned and complementary technologies are used. In addition, the optimization model in Weinand et al. [8] considers extreme days on which demand is particularly high and no wind or solar radiation is present.

4.4. Time structure and pathway

In this section the time horizon (section 4.4.1), the chosen temporal resolution (section 4.4.2) and the pathway for the energy system transition (section 4.4.3) are demonstrated.

4.4.1. Time horizon

The time horizon in the case studies is usually chosen between 15 and 25 years, which represents an appropriate choice for estimating total discounted system costs or LCOEs for an energy system. However, there are also variations upwards and downwards: Adamarola et el. [29] and Drydale et al. [53] even consider 35 and 45 years respectively. Jenssen et al. [71], Moeller et al. [95], Oldenbrock et al. [100], Østergaard and Lund [101] as well as Šare et al. [117] consider one year whereas Kandil et al. [75] use only a time horizon of 24 hours. For the latter study, a time horizon of 24 hours could be too short, even though only the operating costs of an autonomous energy system are determined. At least an extreme day should have been considered for this analysis.

4.4.2. Time resolution

The time resolution of models is of particular importance in studies on energy autonomy. This is especially true for completely autonomous energy systems (cf. section 4.3). Non-optimal design of balanced energy autonomous systems could be compensated by imports from surrounding energy infrastructures. This does not apply for complete autonomy. Therefore, a particularly critical assessment is made when off-grid energy systems are designed on the basis of an annual energy balance, as it seems in Stephen et al. [123]. Stephen et al. [123] investigate the residential and commercial energy supply for an off-grid Canadian aboriginal community. There are also other examples with a very rough time resolution, but these studies only consider balanced autonomy: Jenssen et al. [71] and Peura et al. [105] also conduct an annual balancing of energy (i.e. one time step) whereas the optimization model of Schmidt et al. [118] is based on two seasons (winter/summer) per year (i.e. two time steps).

In almost all studies (91, 74%) the time resolution is set to hours. There is only one study with a higher time resolution, namely Kötter et al. [79] with 15-minute time steps. Kötter et al. investigate the balanced energy autonomy of a region consisting of 17 sub-regions in Germany. However, it is not clear how many of the 15-minute time steps are used in the analysis. The robustness of results on completely autonomous energy systems based on models with hourly resolution must at least be questioned. In these cases it is even more important to consider the methods explained in the previous section, such as LPSP or extreme conditions. In addition, energy systems based on base-load capable technologies such as biomass can be considered more robust than those based only on volatile energy such as wind or photovoltaics (PV) (more on this in section 4.5). Usually all hours of a year are considered in the investigations with hourly resolution (59 of 91, 65%).

Overall it seems, however, that the number of time steps decreases with the complexity of a model, presumably in order to avoid computing time problems: the RE³ASON model based on public data uses only 288 [93] or 432 [8] time slices and the multi-objective optimizations of Fuentes-Cortés and Ponce-Ortega [55] or Yazdanpanah Jahromi et al. [125] use only 96 and 744 time slices respectively. Another example is the optimization with *multi-tier targets* (e. g. scenarios with different demands) according to the *World Bank Global Tracking Framework* by Fuso Nerini et al. [57], which comprises only 18 time steps per year. This is a general problem of energy system analyses. However, as mentioned above, the number of time steps is more crucial in energy system analyses including complete energy autonomy.

4.4.3. Pathway

Energy autonomy projects are always associated with the objective that the energy system will become energy autonomous in the medium to long-term future. This means that there will be a *transition* over several years. However, in almost all reviewed studies (115, 94%), *overnight* is chosen as the pathway, i.e. the new energy system replaces the old one immidiateley and not during several years. This would correspond to an inaccurate calculation of total discounted system costs or LCOEs, as demands and costs may change during the considered time horizon. Only in Dorotić et al. [52], Drysdale et al. [53], Fuso Nerini et al. [57], Krajačić et al. [80], McKenna et al. [93] and Weinand et al. [8] was the pathway modeled as a transition. Dorotić et al. [52] seem to simulate at least every second year in EnergyPLAN from 2011 to 2030. The CO_2 emissions of the system are decreasing and the renewable energies share is increasing until they reach their minimum (0% CO_2 emissions) or maximum (100% renewable energies share) values in 2030. Drysdale et al. [53] also use the EnergyPLAN model. However, they seem to simulate only two years, 2016 and 2050. Fuso Nerini et al. [57] apply the system optimization model

OSeMOSYS for a case study village in Timor Leste. The authors seem to optimize every year from 2010 until 2030. However, as mentioned above, for each year only 18 time steps are considered (six per day and three seasons per year), i.e. 360 time steps in total. Thereby the demand changes during the time horizon. For example, it is assumed, that the households reach the *target tier* in 2025. The target tier would be one of five tiers: for example the households would get access to general lighting, air circulation and television in *tier-2* or small appliances in *tier-3*. In the H_2RES model in Krajačić et al. [80] every fifth year from 2005 until 2015 is simulated. The same applies to the RE³ASON model in McKenna et al. [93] and Weinand et al. [8] (time horizon from 2015 until 2030). In the two latter studies, however, the method is a mixed-integer linear optimization: all four years are optimized simultaneously, i.e. it is decided when which plant or measure will be installed. By considering the existing infrastructure (e.g. already installed PV modules), as in the RE³ASON model, models are enabled to consider a transition pathway.

4.5. Technologies

As already discussed in section 4.1, many case studies on energy autonomous remote rural areas deal with the reduction of diesel and the increase of renewable energies in the system. As shown in Table 9, diesel, therefore, is the most frequently considered in the studies after PV, wind and stationary batteries. A total of 73 studies (59%) consider conventional generation technologies such as diesel generators and gas fired CHP / turbine plants in their energy system analyses.

When classifying biomass CHP, hydropower plants, deep geothermal plants as well as conventional generation technologies as baseload-capable, 26 studies (21%) remain, in which only volatile generation technologies are considered. In 16 of these 26 studies, no long-term storage options such as hydrogen storage, pumped-hydro-storage or power-to-gas are considered. In such cases, it is essential to take account of uncertainties. In ten of the 16 studies [35–37,66,70,85,91,115,116,134], these uncertainties are at least addressed via LPSP and in another study [103] by including extreme conditions. Even more than in other studies, the results of the completely autonomous energy systems in Al-Shetwi et al. [32], Khan et al. [76], Kim et al. [77] and Mas`ud [137] must therefore be questioned, in which only volatile energy technologies and no uncertainties are considered.

The fact that so few studies examine heating or cooling technologies (cf. Table 9) is related to the focus on electricity in the studies (cf. section 4.2.2). In addition, technologies that do not belong to the standard technologies such as PV or wind are primarily investigated in case studies in HIC in Europe. For example, the technologies deep geothermal energy, power-to-gas or district heating are analysed primarily in Germany (deep geothermal energy: [8]; power-to-gas: [79,95]; district heating: [8,71]) or Denmark (deep geothermal energy (only heat): [101]; district heating: [53,101]), while unconventional vehicles such as EVs [52,53,117] or fuel cell vehicles [80,100,141] are examined primarily in case studies in Croatia. This suggests that the studies on remote rural areas are primarily concerned with the electrification of the area and not with the choice of optimal energy technologies. On the other hand, technologies such as deep geothermal energy (despite high potential in e.g. India or Sub-Saharan Africa [389]) are not relevant for these rather small regions (see section 4.2.1) due to high fixed costs [8].

Table 9: Classification of the technologies included in the reviewed literature as well as the frequency of their consideration.

Category	Technology	No. of studies
Renewable electricity generation technologies	PV	117 (95%)
	Wind (onshore)	85 (69%)
	Biomass CHP	39 (32%)
	Hydropower plant	21 (17%)
	Concentrated solar power	3 (2%)
	Deep geothermal plant	2 (2%)
Heating / cooling technologies	District heating / cooling	10 (8%)
	Heat pump	7 (8%)
	Solar thermal collector	6 (5%)
	Electric heater	6 (5%)
Storage technologies	Stationary battery	93 (76%)
	Hydrogen with fuel cell	18 (11%)
	Thermal	8 (7%)
	Pumped-hydro	4 (3%)
	Power-to-Gas (methanisation)	2 (2%)
Transport technologies	Electric vehicle (modelled with battery)	3 (2%)
	Fuel cell vehicle	3 (2%)
Conventional generation technologies	Diesel generator	63 (51%)
	Gas fired CHP	6 (5%)
	Gas turbine plant	6 (5%)

In summary, the studies on local energy autonomy investigate a wide range of technologies. However, for a robust design of an energy autonomous system based on renewable energies, the combination of fluctuating and non-fluctuating generation technologies as well as different storage technologies could be advantageous. Some of these technologies that could be beneficial in a completely autonomous case, such as seasonal heat storage, have not yet been analysed. In general, the more diverse the technologies under consideration, the more economically or environmentally sustainable the energy system could be designed. On the other hand, the complexity and computing time of energy system models increases with the number of technologies. In any case, work still needs to be done in which a very broad range of technologies is considered and the optimum technologies for energy autonomy are identified. Based on the results of the reviewed studies, no definite trend towards the most economic technologies for achieving energy autonomy can yet be identified (cf. section 4.7).

4.6. Grid infrastructures

Grid infrastructures are rarely modeled in the studies. Heating grids are implemented only in [8,93,113], the electricity grid only in [8,31,93,95]. In [27,78] at least the costs for setting up the distribution network are taken into account. It is interesting to note that all four case studies that consider the electricity grid are located in Germany. In [8,93] the electricity and heating network is only represented in a simplified way by energy flows between districts. However, Weinand et al. [8] also contains a transferable approach for designing district heating networks in arbitrary municipalities. District heating systems are also designed in Sameti and Haghighat [113]. While in [8] the district heating network is modelled top-down for entire municipalities, [113] is better suited as a bottom-up application for districts for which exact building locations and energy demands are known. Therefore, depending on the application, the two studies offer possible approaches for future analyses.

In Moeller et al. [95], the capacities and connections of the electric transmission network between German regions are modeled. The analysis also examines whether the transmission capacities are sufficient, depending on the share of renewable energies. In the FlexiGIS model in Alhamwi et al. [31], OpenStreetMap is used to obtain data on lines and substations of the distribution network in order to determine the optimal placement of a battery storage in an urban area. Unfortunately, power grid data is not yet completely included in OpenStreetMap and therefore this method is not usable for every case study.

Electricity grids are only considered in a simplified way in the papers. A promising approach for future studies could be the one of Morvaj et al. [156], in which the distribution network is modelled according to a linearized AC power flow approach. Of interest is the implementation of a binary modelling variable, which determines whether the distribution grid needs to be upgraded, depending on the amount and type of renewable energies added to the energy system. In the case of an upgrade, the expansion of renewable energies would involve additional costs. However, the study uses available grid data of the *IEEE European Low Voltage Test Feeder case* [390]. Since this grid data is not available for arbitrary case studies, the grid capacities would have to be estimated.

4.7. Costs

Section 4.1 has already shown that the energy systems in the literature were mostly designed on the basis of cost minimization. Therefore, a comparison of these costs is reasonable. In 83 (68%) of the 123 studies, the LCOEs for autonomous energy systems were stated (cf. Figure 2). For Figure 2, the LCOEs from the studies were adjusted according to inflation until 2019 [391] and converted into $/kWh using the average exchange rates [392–394] in the year of the respective publication. As all but one of the 83 studies consider the residential sector, the household electricity price (import from grid) in the different countries is shown for comparison [395]. For eight countries (e.g. Ethiopia [67] or Yemen [32]), the household electricity price could not be found.

The mean LCOEs amount to 0.41 $/kWh (black dotted line in Figure 2). Consequently, the costs in the studies of Khan et al. [76] and Hosseini et al. [66] are nearly average. The LCOEs in an energy system with 100% renewable energy are on average 0.42 $/kWh (0.37 $/kWh without the outlier in Askari and Ameri [35]) whereas in an energy system with conventional energy 0.39 $/kWh (0.36 $/kWh without the outlier in Shezan et al. [122]) is achieved. As expected, in studies considering both cases, the LCOEs of 100% renewable energy systems are higher than of conventional energy systems. Likewise, the LCOEs decrease if cases with security of supply below 100% are considered. Furthermore, the household electricity prices are lower than the LCOEs for the autonomous system for almost every study. The only exceptions include case studies in countries with above-average electricity prices (Australia [41], Croatia [52] and Germany [79,95]), or the two studies with the lowest LCOEs [110,113] in Figure 2.

18 out of the first 20 upward outliers in Figure 2 apply the HOMER model (for the other two, the applied model cannot be found in the article), i.e. a non-optimal design of the energy system could be responsible for the high LCOEs (cf. section 3.1). In the following, the three studies from Figure 2 with the highest upward outliers in the LCOEs are discussed (up to the study Li et al. [83] with 1.57 $/kWh on average). The highest LCOEs in the study by Askari and Ameri in 2009 [35] are caused by the high inflation in Iran between 2009 and 2019 (+364%). As a result, the costs are adjusted from originally 0.75 $/kWh to 3.27 $/kWh. The study by Shezan et al. [122] with the high LCOEs of 2.01 $/kWh needs further investigation, especially since an unmet load of 0.01% is considered here, which should reduce the LCOEs. Unfortunately, by analysing the study it is not really possible to determine

how the HOMER model achieves the high LCOEs for the most economic energy system with PV, wind, diesel generator and stationary battery. However, surprisingly, a figure in the study shows more realistic HOMER results with LCOEs of 0.62 $/kWh, but these LCOEs are not discussed further in the text. In Li et al. [83] the predefined design of the energy system seems to lead to the high LCOEs of 1.54 $/kWh. In fact, an energy system with 500 kW of PV and 9.1 MWh of stationary batteries is assumed for 100 households in China. This energy system appears to be oversized, which again demonstrates the need for a good understanding of the energy system when designing energy systems with HOMER (cf. section 4.1). In addition, the PV-battery system is compared with a PV-battery-fuel cell system, but the capacities of PV and battery are not changed. Thus, it is obvious that the PV-battery system leads to lower costs.

The reason for the low LCOEs for energy autonomous systems of the downward outliers is more difficult to determine and would require an in-depth analysis in a separate study. In the case study in Rajanna and Saini [107], for example, there is great potential for baseload hydropower and bioenergy, which could be related to the low LCOEs of 0.07 $/kWh. Examining further studies for reasons related to LCOE would be beyond the scope of this literature review. However, the detailed table in the online appendix could be used in further studies to investigate the dependencies of the LCOEs on the characteristics of the studies, e.g. through cluster or regression analyses. The online appendix and Figure 2 are useful as a basis for evaluating future studies about local energy autonomy. If, for example, the LCOEs deviate as much from the average of 0.41 $/kWh in future studies as in Li et al. [83], the applied methods and results have to be further investigated.

Since most of the studies calculate LCOEs, these figures are very suitable for comparing the results of local energy autonomy studies. However, another cost parameter that is particularly relevant for the inhabitants who have to pay for the costs of the autonomous energy system is rarely shown in the studies: total costs per inhabitant. These are only shown in Jenssen et al. [71] (1.4 – 2.3 k$), Schmidt et al. [118] (220 $/a more than in the reference scenario without autonomy) and Weinand et al. [8] (21.0 – 54.8 k$). However, the cost per inhabitant should be included in all future studies in order to assess the feasibility of the energy autonomy project.

In some studies, the costs of the completely autonomous energy system are compared with the costs of grid connection [34,88,98,102,112,131]. In all examples, the grid connection scenario turns out to be less economical. This is due to the fact that these studies only consider remote areas that are far away from the nearest grid connection point. The break-even points for the distance from which the network connection would be worthwhile are calculated in [88,102,112,131]. This is also related to the question of the optimal degree of centralization as well as the optimal size of energy autonomous municipalities (cf. section 5).

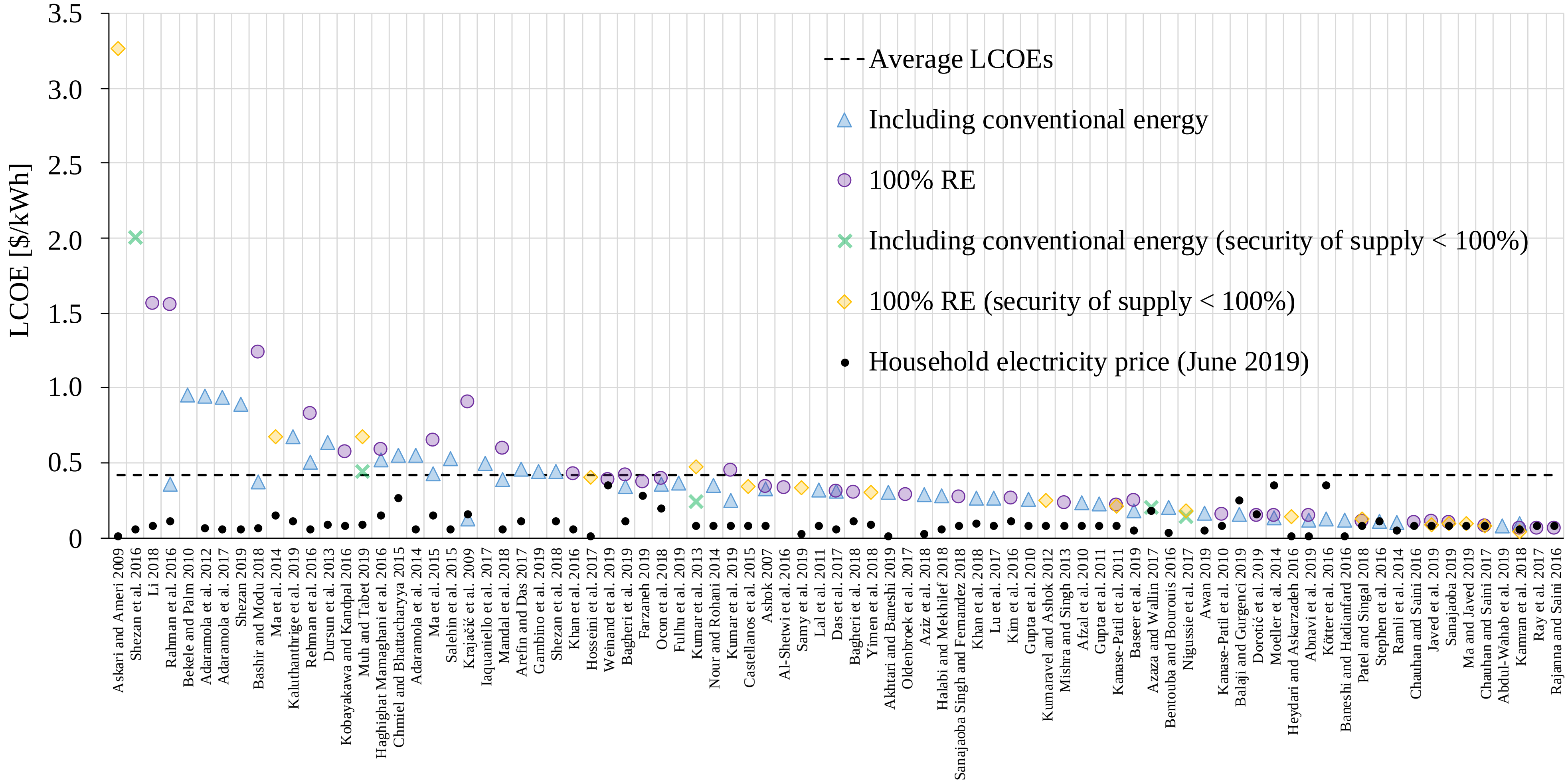

Figure 2: LCOEs of the energy autonomous case studies in the literature. The studies are sorted by mean LCOEs, from high to low. The LCOEs were adjusted according to inflation until 2019 [393] and converted into $/kWh using the average exchange rates [394–396] in the year of the respective publication. The household electricity price (black dots) in the different countries is shown for comparison [397]. The black dotted line shows the average value (0.41 $/kWh).

5. Critical appraisal of energy autonomy studies

In this section, some of the key findings of section 4 are subjected to further critical evaluation. Firstly, though it is difficult to generalize across all 123 reviewed studies, some emerging trends may be highlighted:

- Mostly conventional/established technologies are analysed, with less attention paid to emerging but potentially game-changing technologies such as deep geothermal and fuel cell vehicles;
- The sectoral focus is on residential, with much less consideration of industrial and transportation sectors;
- Network infrastructure is rarely considered, including electricity, gas and heat/cooling;
- Only a minority of studies account for the existing infrastructure as well as the transition from this state to some improved future state along a transition pathway;
- Most studies focus on complete energy autonomy, with some (12%) dealing with balanced energy autonomy.

The time resolution of most studies is hourly, with one study going into more detail at the 15-minute level. For long-term planning purposes, the hourly resolution is suitable, but it should also be combined with more detailed analyses and/or information reduction techniques to generate time typologies and synthetic time slices. There is an established stream of research focussing on the most suitable/required time resolution for specific research questions, for energy systems with significant renewable generation fractions (e.g. [396,397]). Studies addressing regional and local energy autonomy could also benefit from exploring such approaches. Otherwise there is a danger that systems are incorrectly dimensioned and are inadequate to ensure supply security in times of peak demand, which for autonomous/off-grid systems is potentially critical.

There is also a lack of attention paid to non-economic and non-technical criteria in studies of energy autonomy at the local scale. Indeed, economic criteria are arguably the most important, but although they are necessary, they are not sufficient. In section 1, among others, it has already been highlighted that certain areas are very far from the national grid and therefore a stand-alone system is appropriate. In this case, the focus on costs as a target criterion is justified, however, the comparison of complete autonomy with the grid connection case should always be demonstrated. Otherwise, in future analyses of energy autonomy more criteria than costs need to be considered. There are other important reasons for municipalities to become energy autonomous besides costs, such as increased environmental awareness (cf. section 1). Furthermore, a comparison with the electricity price in section 4.7 shows that energy autonomy usually leads to significantly higher costs, and thus from a cost perspective there is no potential for energy autonomy.

In terms of the modelling approaches employed for highly renewable, autonomous energy systems there is a clear dominance of linear programming (i.e. optimization) and simulation (i.e. dispatch rules for energy balancing), from a central planner perspective. It is encouraging to find that many researchers are also capturing the non-economic criteria such as health, noise, water and acceptance issues (cf. Table 7). However, these contributions are still in the minority of those reviewed here, and the overwhelming majority do not satisfactorily reflect the true complexity encountered in real-world energy transitions. It is common practice to leave stakeholder roles outside the scope of the studies or models and to calculate optimal autonomy transition pathways with a centralized planning approach under the selected objective of technical feasibility and economic viability. However, local energy systems are complex socio-technical systems consisting of different decision-making entities and technological artefacts governed by energy policy in a multi-level institutional space [12]. Social relationships among the stakeholders represent a major driver or barrier as also stated by previous reviews [4]. In this context, adoption behaviour approaches are useful to understand the types of barriers that exist for new technologies, and what kind of policies are important to increase diffusion. As a consequence, realising the potential of local energy autonomy is not simply a question of technical realities but also a question of individual behaviour and group dynamics. Relevant local stakeholders as households or communities, energy producers, energy suppliers, service providers, as well as local policy-makers are inter-dependent in the realization of their goals. Future system models need to include the heterogeneous roles different stakeholders play in an existing local environment and the resulting impact their decision making might have. One possible solution could be the extension of the presented techno-economic modelling approaches with the help of socio-economic modelling approaches as agent-based models [398,399] or system dynamics models [400].

Many different spatial scales (e.g. number of households) have been considered in the case studies (cf. section 4.2.1). Whilst the optimal spatial size of an energy autonomous region has not yet been identified, it is interesting to note that the mean number of households and inhabitants in energy-autonomous regions is 340 and 18,200, respectively (based on the 56 and 49 articles containing this information, respectively). This is strongly linked to the question of the optimal degree of centralisation [401]. Concerning demand and consumption sectors there is also some potential for improvement (cf. section 4.2). The demand product water, for example, which is strongly linked to energy, or the consumption sector industry is only very rarely taken into account. For the latter, transferable methods to determine the energy demand and load profile of industries in arbitrary regions could facilitate its implementation. The transport sector is also almost completely ignored in studies about local energy autonomy. A particularly interesting approach would be to optimize the number and use of electric or fuel cell vehicles. In general, however, all sectors should be taken into account, especially when estimating the impact of one or many energy autonomous regions on the surrounding energy system.

Validation is challenging in the context of local energy systems, which might explain why very few existing studies attempt to do this. Often detailed data on the existing energy system is lacking and validation for some hypothetical future scenario is obviously not meaningful. Model design and data assumptions of studies used to gain insights to form the decision making should be transparent and accessible. This not only allows independent review of various stakeholders but also the complete reproducibility of the results [402]. Whilst there is a strong trend towards open-source models and data within the wider energy system modelling field [403], of the reviewed models, none appear to be fully open source, with Homer and EnergyPlan only being open access. Hence local energy autonomy studies could increase efforts to publicly release data and system models as well as assumptions and results interpretation, in order that diverse affected stakeholders are able to participate in the decision-making process [402,404].

In addition, the focus on the LCOEs as a benchmark for highly-renewable energy systems could provide potentially misleading results. Whilst the LCOE is a good first indicator of the generation costs and allows comparisons across technology, it is noted for neglecting the additional costs of integrating non-dispatchable renewable technologies into the energy system. Three additional cost components should be considered, if the true *system LCOEs* of renewable energy technologies are to be considered [405,406]:

- **Profiling costs**, related to the requirement for the dispatchable generation technologies to meet the residual load;
- **Balancing costs**, related to the deviation between forecast and actual non-dispatchable renewable generation; and
- **Grid costs**, related to addition grid reinforcement and extension (at all voltage levels) required to connect renewable generators to the network.

Attempts have been made to consider these cost components in the context of large-scale (e.g. national) energy system analyses (e.g. [407–409]). However, at the regional and municipal scale, as demonstrated by this review, they are typically not included. This is despite the fact that, when considering balanced autonomy, these effects on the surrounding energy system are of particular importance. Balanced energy autonomy and the associated increasing feed-in by renewables could make network expansion even more essential and also make new allocation systems for grid fees necessary [401]. The result could be economic inefficiencies compared to the established system of centralised generation, transmission and distribution [410]. However, possible energy system impacts were not considered in any of the 14 studies on balanced autonomy. Hence there is a need for further research to address these and the above mentioned deficits.

6. Summary and conclusions

Research attention on decentralized autonomous energy systems has increased exponentially in the past three decades, as demonstrated by the absolute number of publications and the share of these studies in the corpus of energy system modelling literature. This paper shows the status quo and future modelling needs for research on local autonomous energy systems. A total of 359 studies are roughly investigated, of which a subset of 123 in detail. The studies are assessed with respect to the characteristics of their methodology and applications, in order to derive common trends and insights.

The results show that most case studies were conducted in the middle-income countries India, Iran and China as well as the high-income country Germany. In the middle-income country studies, mostly remote rural areas without electricity network connection are considered, whereas in high-income countries the case studies are much more diverse and also include cities and islands. In addition, most studies only focus on the residential sector and the supply of electricity. A wide range of technologies has already been covered in the literature, including less common technologies such as power-to-gas and fuel cell vehicles. However, the network infrastructure is rarely considered. The levelized costs of electricity for local autonomous energy systems in 83 case studies amount to 0.41 $/kWh on average. Thereby, studies are identified in which the resulting costs should be questioned, as they deviate strongly from the average.

In terms of the employed methodology, most of the reviewed literature reports an optimization or simulation approach, with a central planner perspective. They typically employ a time resolution of one hour, but for some studies also increase this to 15-minute resolution. Whilst it is commendable that some of the studies also consider non-economic criteria such as social and environmental aspects, neither the system-level impacts nor the diverse stakeholders are included in most works. Furthermore, there is a general lack of transparency across most reviewed literature, meaning that neither open data nor open models are widely applied to local energy systems.

Hence, future research should focus on the following methodological innovations. Other perspectives than that of a central planner and other target criteria than costs should be included. This could contribute to the realizability of the case study results. System impacts of many local autonomous energy systems have not yet been investigated, which could make new distribution systems and grid fees necessary. Complete autonomous energy systems in particular must be robustly designed, for example by analysing the value of lost load and whether a security of supply below 100% is acceptable for consumers of the case study, preferably using penalty costs for unmet load in the target function. In addition, extreme conditions such as extreme days with low solar radiation or wind should be considered and the temporal resolution should be higher than the usually used hourly resolution. Finally, methodologies should be developed which can involve local stakeholders in the modelling process and thus consider their preferences relating to their future energy system.

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