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Improving understanding of energy autonomy: A systematic review

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A R T I C L E I N F O

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A B S T R A C T

Autonomy is often cited as a key aspect of energy systems. Previous academic literature on energy autonomy has predominantly approached it from a technological perspective, and conceptualized it as self-sufficiency of energy production. In addition to self-sufficiency, autonomous energy users and communities often aim to create energy systems that treat different stakeholders as equals, with a balanced distribution of costs and benefits. This paper has two aims. First, it aims to clarify the concept of 'energy autonomy'. Second, it aims to provide an overview of existing literature addressing energy autonomy, identifying relevant publications and publication outlets, as well as main research themes and activities. The results, based on a systematic review of 71 peer-reviewed academic articles, show that energy autonomy research has increased in the last twenty years. The results also show how existing literature has understood, and used, the concept of energy autonomy in varying ways. Furthermore, the paper reveals how motivations, technologies, and scales differ in energy autonomy projects. While the aim of reaching energy autonomy is often motivated by economic and/or social reasons, these aspects are nevertheless rarely discussed in academic literature as the predominant focus tends to be on technological issues and self-sufficiency. The paper concludes with energy policy implications and avenues for future research.

1. Introduction

Renewable energy systems (RESs) are profoundly changing how energy is produced, distributed, and consumed. These systems, supplying electricity and heat on different scales, can potentially disrupt the existing economic and social organization of energy provision. The transition to renewable and decentralized energy production has been proposed as a solution not only for dealing with climate change but also for increasing self-sufficiency in energy provision [1]. In relation to this, the concept of "energy autonomy"—that is, the ability of an energy system to be fully functional through its own local production, storage, and distribution systems while simultaneously fostering local environmental and social goals [2]—has been seen as a potential way of creating a sustainable, low-carbon energy system.

Several examples of energy autonomy exist in communities, islands, and cities that seek local energy self-sufficiency by employing renewable energy and storage technologies. Such examples include, for instance, microgrid projects in the Dutch cities of Amsterdam and Olst, renewable energy in the Danish commune of Thisted and the island of Samsø [3], and bioenergy in the Austrian rural towns of Güssing and Mureck [4]. Further, numerous academic studies have examined energy autonomy. A recent strand of research on energy autonomy has, for example, examined different scales and various technologies—including solar photovoltaics (PV) and wind power—and their capabilities with regard to energy autonomy provision.

The analysis of energy autonomy has often been extended beyond technical and economic factors to include an analysis of social feasibility. It has also been understood as a direction that leads toward creating greater self-sufficiency rather than a strict requirement that assumes total self-sufficiency [5]. The vast majority of energy autonomy research has been based on simulations undertaken, for example, at the regional level, typically for islands. Previous research on energy autonomy has, however, often involved different methods and technologies, resulting in a lack of formalization or consistency regarding what energy autonomy actually means [6]. A systematic review of literature is thus called for if we are to understand the complex socio-technical aspects that form energy autonomy. There is also a need for a holistic understanding of what energy autonomy implies and how it can be achieved, especially as we move toward net-zero societies that are expected to use an increasing number of decentralized renewable energy systems.

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List of abbreviations

CHP	Combined heat and power
CO_2	Carbon dioxide
DIY	Do-it-yourself
LCOE	Levelized cost of electricity
m(CHP)	Micro combined heat and power
NIMBY	Not in my backyard
PV	Photovoltaics
QCA	Qualitative Comparative Analysis
RES	Renewable energy system
ZEB	Zero energy buildings

The aim of this article is to provide an understanding of the concept of energy autonomy through a systematic review of peer-reviewed academic literature, covering the period from 2000 to 2018. It provides a comprehensive overview of how energy autonomy has been approached and defined in different strands of the energy research literature, with the aim that this overview will also benefit future research. The paper is arranged as follows. Section 2 outlines the methods used, including details of the systematic literature review and thematic analysis. Section 3 presents findings, while Section 4 discusses the results. Section 5 outlines conclusions and the final section provides directions for future research.

2. Methods

2.1. Systematic literature review

To understand different aspects of energy autonomy and how the concept has been technically and socially constructed, a systematic review of previous literature was conducted to comprehensively identify, assess, and synthetize relevant between 2000 and 2018 [7]. The literature search and analysis were guided by the following research questions: 1) What is meant by energy autonomy? 2) How is energy autonomy constructed as a socio-technical concept?

To ensure rigor, a three-stage approach was taken to ensure a systematic search process (see Section 2.2, below), following the principles outlined by Tranfield et al. [8]. In order to make the search process transparent and enable possible replication by other researchers, the search strategy is fully elaborated in Section 2.2, below.

2.2. Search process

The literature search consisted of three distinct stages:

Stage 1: First, a need for a review was identified using Google Scholar and Web of Science to see if there had been previous systematic reviews of energy autonomy literature in English peer-reviewed journals. This search found only one such study, by Rae and Bradley [2], which focused on energy communities. However, other articles in the search indicated that the concept of energy autonomy can extend well beyond communities. From this, it was concluded that there had been no broader previous systematic reviews on energy autonomy and that a review considering energy autonomy at different scales (e.g., cities or local regions) would be useful.

Stage 2: In second stage, a systematic search was conducted, starting with the identification of the most appropriate keywords and search terms for the study. A strict criterion was used to ensure the inclusion of best-quality evidence. This meant a structured approach to reviewing original academic research published between 2000 and 2018, and using the databases of *ScienceDirect*, *Scopus*, and *Web of Knowledge*. To ensure validity and high academic rigor of the research identified, only *peer-reviewed journals* were included in the review. To ensure the inclusion of studies that focus on energy autonomy only, the search criteria was limited to title, abstract, and keywords, and within journals in *energy, environmental*, and *social science*. The search begun with the keyword “energy autonomy”, but based on the first round of results—which were114[1]— keywords “energy autarky”[2] and “energy sovereignty” were added.

Stage 3: Third stage involved conducting the focused systematic review and analyzing data. The search was started in the ScienceDirect database, which resulted in 53 articles with the three keywords (energy autonomy, energy autarky, energy sovereignty). This was then extended to the databases Scopus and Web of Knowledge, which resulted in further 42 and 58 articles, respectively. Duplicates, book review articles, non-English outputs and articles that did not specifically address the energy sector were removed, which resulted in a total of 71 unique articles. Table 1 summarizes the details of the article searches.

Next, article titles and abstracts were screened, and a database of all relevant articles was created. Following this, the articles were first analyzed descriptively, and as a final step, thematically (see Section 3). The thematic analysis was based initially on an inductive approach to coding articles, but this then evolved into a combination of inductive and deductive coding. The main deductive codes for each article included the following five key topics: 1) energy autonomy definition, 2) which literature the paper makes a contribution to, 3) empirical or conceptual approach, 4) methods, and 5) sources of data. Further seven theoretical deductive codes were also introduced, including: 1) technical application, 2) scale, 3) inclusion of economic aspects, 4) inclusion of social aspects, 5) empirical paper, 6) conceptual paper, and 7) a combination of empirical and conceptual. In addition to these predetermined codes, other codes emerged during the analysis, such as temporality and motivations.

In order to analyze technologies that are used to create energy autonomy, configurational methods [9,10] were also applied to examine the articles for the following two reasons: First, multiple energy sources and technologies are necessary to achieve energy autonomy when renewable energy technologies based on intermittent energy sources are used. Second, energy autonomy features equifinality [10], i.e. multiple combinations of technologies or technological pathways can lead to energy autonomy on certain scales and within certain time spans. To identify the combinations most widely used in research, which might also demonstrate intuitively the most promising avenues with regard to the quest for energy autonomy, statistical analysis software R with R packages Qualitative Comparative Analysis (QCA) and SetMethods [11] was used to create and optimize truth tables [12] of generating technologies and storage options that are used in combination in case studies in the literature.

Table 1
Summary of the literature review.

Keyword	ScienceDirect hits	Scopus hits	Web of Knowledge hits	Unique articles
Energy autonomy	41	30	43	54
Energy autarky	8	8	7	9
Energy sovereignty	4	4	8	8
Total	53	42	58	71

[1] This number includes duplicate articles which were removed on next stage.

[2] We initially included the keyword “energy autarky” in the search. But, as one of our reviewers pointed out that this term is more commonly used in German than in English research, while we report the number of articles found using “energy autarky” we base our findings and analysis on results for the keywords “energy autonomy” and “energy sovereignty”.

2.3. Study limitations

This review was a first attempt at providing a broad overview of how the concept of energy autonomy has been approached in previous literature. It was not meant to be an all-compassing study on the topic, which notably leaves some limitations. First, the systematic review was limited to articles in the English language only, which leaving out any articles published on energy autonomy in any other languages. Second, in order to manage the number of articles within the allocated research project time, the search was limited to three academic databases. Third, as a first broader review of energy autonomy literature, this review only examined articles' content and did not include details of authors' gender, cultural setting, academic tenure or funding sources, for instance, all of which could influence the type of research that is being conducted on energy autonomy. The authors would therefore welcome further research from different angles on the topic, including also multiple real-life case studies, and both qualitative and quantitative methods.

Following the systematic literature review and coding process, the concept of energy autonomy is examined in more detail in Section 3, focusing on the following main themes: scale, motivations, technologies, time spans, economic aspects, and social issues.

3. Results: systematic literature review

This section provides the results of the systematic literature review on energy autonomy. It starts with an overview of energy autonomy literature and a conceptual discussion on what energy autonomy entails at different levels and/or in different domains. The section then moves on to the main themes identified by the review, including scale, motivations, technologies, and considerations for time spans, as well as how economic aspects and social issues have been presented in the literature.

3.1. Energy autonomy in energy research: a bird's-eye view

Energy autonomy has been attracting increasing and steady interest from academic research for the past 20 years. At the turn of the millennium, there were typically one or two articles published each year, increasing to 10–14 academic articles towards the years 2016–2018 (see Fig. 1).

Academic journals *Energy Policy*, *Applied Energy*, and *Renewable Energy* have been the main outlets for the publication of energy autonomy research. Seven journals returned more than two articles on energy autonomy, indicating that it has been an ongoing subject of interest in these journals (see Fig. 2).

3.2. Conceptual development of energy autonomy

In terms of the concept of energy autonomy and how it is defined, energy independence or self-sufficiency, and the creation of autonomy—and how users, communities, municipalities, or nations can achieve it—has been discussed under different names in energy research. The most commonly used concepts are "autonomy" [1], "sovereignty" [13,14], and sometimes "autarky" [15]. Although all these concepts share a similar basic tenet of aiming for a balance between self-sufficient energy consumption and production, the concepts have different legacies and conceptual developments over time.

The term energy autonomy emerged in academic literature in the early 1990s when new renewable energy technologies, such as solar PV, were installed in homes and public buildings [16]. For example, in 1992, a seminal development took place when the Fraunhofer Institute for Solar Energy Systems built an energy autonomous house in Freiburg, Germany [17]. The institute aimed for a self-sufficient building, wanting to understand the possibilities and limitations of decentralized energy generation. This illustrates well how one of the central tenets of energy autonomy has, from the start, been self-sufficiency.[3] Since 2010, however, the notion of self-sufficiency has been considered as too narrow, and social aspects have been recognized as other important issues, widening the scope of literature on this topic.

Even though the term energy autarky has not been as widely used as energy autonomy, it is included here briefly as it has been used in the literature for at least as long as the term energy autonomy, to also refer to self-sufficiency [18]. Müller et al. [15] introduced the idea of energy autarky in 2011 as a conceptual framework for sustainable and regional development. They adopted a slightly different viewpoint, using a holistic approach that went beyond self-sufficiency by emphasizing the interdependencies between energy and the triple bottom line of sustainability—that is to say, environmental, economic, and social objectives—within a region. This concept also includes the issue of process; and how civil society, policy and governance [15], or security [19] viewpoints should be involved in the process of achieving an autarkic energy system. Soon after the publication of the Müller et al. article [15], the energy autonomy concept was broadened by Rae and Bradley's work on community energy in 2012 [2]. From this point onward it can be said that the terms energy autonomy and energy autarky overlap and have been used interchangeably.

The review shows, that in a limited number of studies, the term "energy sovereignty" is used instead of energy autonomy or energy autarky. Dell'Anna and Menconi [20], for example, examine energy sovereignty in rural areas and underline the concept's social dimensions. Energy sovereignty recognizes "energy as a human right". Additionally, sovereignty seeks to return control to individual energy users and juxtaposes the benefits that are gained by utilities with those gained by citizens [21], highlighting social inequalities embedded in contemporary energy systems [14]. The unit of analysis in energy sovereignty studies ranges from local community and rural regional scales [13] to national-scale energy systems [14,22].

As can be seen, there are no clear differences between the concepts of energy autonomy and energy autarky (overall, the latter has remained a rather limited stream of research [23–27]). The overlapping use of the terms also shows that there is a need to look beyond the aim for self-sufficiency and understand how social organization around energy provision shapes the ability to self-determine energy provision.

Energy autonomy, as a concept, entails political, economic, and technological aspects [1]. While the term is typically linked to the use of renewable energy, it is not limited to merely measuring how much energy demand is met by renewable energy. Energy autonomy also entails social processes, practical strategies, and autonomous initiatives by different actors (e.g., individuals, communities, intermediaries, companies, and municipalities) who work together to change existing energy regimes [1]. In this review, the focus thus is on analyzing the concept of energy autonomy as it is the most widely used term in the literature (though also acknowledging the other relevant terms [e.g., self-sufficiency] and when they essentially concern the same concept).

[3] Hermann Scheer's 2006 book [1] positions energy autonomy rather differently from previous academic research. Being a popular book rather than an academic book, it uses the term to sell the idea of renewable energy as an alternative to fossil- and nuclear-based systems. The book is a sidetrack in the longer trajectory of how interest in and discourse around energy autonomy has evolved.

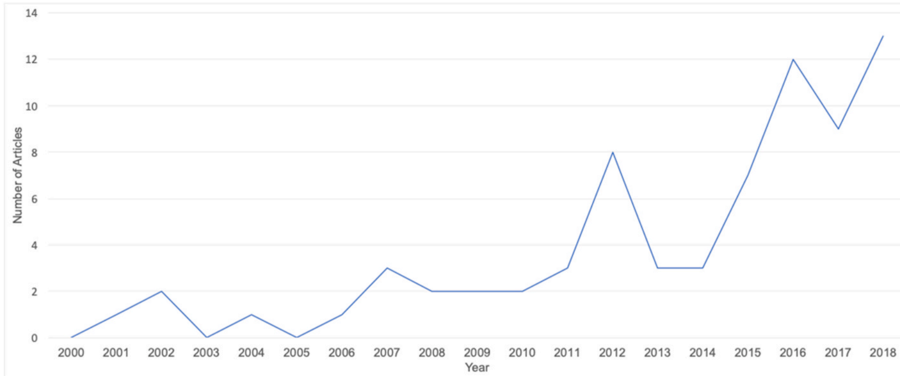

Fig. 1. The annual number of published papers with focus on energy autonomy 2000–2018.

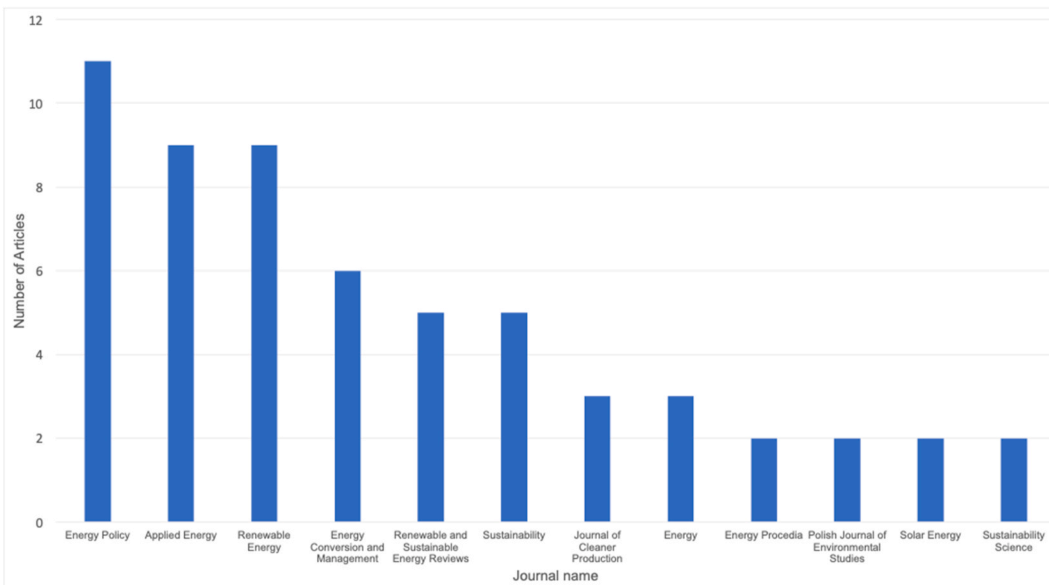

Fig. 2. Number of energy autonomy articles by journal 2000–2018 (frequency >1 article per journal).

3.3. Scales

The systematic review shows that energy autonomy is relevant at different scales, in particular the following five: 1) buildings (both domestic and commercial) [5,13,28–31], 2) neighborhood, 3) community [2,32], 4) regional [33,33–36], and 5) national [37–40] (see Fig. 3). These categories are not easily separable, and overlaps are clearly visible, for example between neighborhood and community scales. Although public discourse and politics often emphasize national-level energy autonomy, the national scale is found less in academic journals. Petrakopoulo [41] limits energy autonomy to "energy production with domestic energy sources". In this review, three papers focused on national-level analysis—namely, Michalena and Frantzeskaki [38] and Kaldellis [40] on Greece, Yue and Huang [39] on Taiwan, and Mastropietro et al. [25] on Europe.

The review found that a regional-scale energy autonomy analysis was the most common approach, including both urban and more isolated rural areas. These studies commonly drew from bounded empirical cases, including isolated areas, such as islands, that by their nature have to be self-sufficient in energy provision. Much of this literature also relies on simulations and scenario building, and these have been conducted, for example, for the islands of Wand-an [42], Guadalupe [43], Corsica [44], Reunion Island [45], and a remote island in Hong Kong [35]. Islands in the Aegean Sea in particular have been the focus of

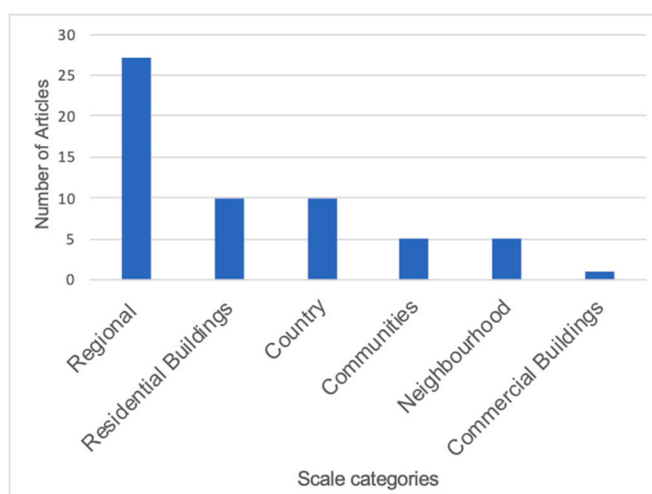

Fig. 3. The number of energy autonomy articles by scale categories.

numerous analyses of energy autonomy, including the Greek islands of Karpahtos [46], Ikaria [46,47], Agathonisi [48,49], Agios Efstratios [49], Anafi [49], Erikousa [49], Megisti [49], Othonoi [49], Andros

[50], Naxos [51], Skiros [51], Skyros [41,52], Kithos [46,47,50,53], Kea [50], Rhodes [54], and Sifnos [55]. Energy autonomy has also been studied at the city level. Tragopoulus et al. [56], for example, see urban energy autonomy as a building block necessary if countries are to move toward geopolitical independence.

The scale of energy autonomy is affected by, and sometimes dependent on, the scale of the chosen technology. Solar PV, for example, is suited to a variety of scales, from single, small-scale household units to large-scale solar parks.

3.4. Motivations

The review found several motivations driving the quest for energy autonomy, including independence from energy markets and utilities, stability in the face of fluctuating energy prices, environmental concerns, and better energy security.

For example, Maes et al. [5] found that local energy initiatives seeking to improve self-sufficiency were motivated by a desire for greater independence from energy markets [5]. Energy autonomy can provide households and communities stability in regards to energy price fluctuations. It can also provide independence from electrical grids, which may in turn result in lower distribution fees and also greater control over local decisions relating to energy systems [2,15,30,57]. Engelken et al. [58] studied why municipalities aim for self-sufficiency, and found that mayors had various combined motivations for pursuing energy autonomy, including environmental awareness, the opportunity to earn extra tax revenues and gain greater independence from private utilities.

The pursuit of energy autonomy has also been driven by energy security. Building resilient energy infrastructures can safeguard resource flows and key energy services from threats such as climate change, terrorism, and warfare [59]. Also, energy autonomy and ownership are highly interlinked. Co-ownership of local energy plants has been found to have a positive effect on public acceptance of renewable energy for example [60,61]. Consequently, this has also led to policy initiatives that favor an energy autonomy agenda in order to scale up low-carbon energy technologies [61].

3.5. Technologies

Previous literature on energy autonomy has mainly centered on the applicability of technology, and especially on how certain technological combinations, over a certain period of time, could create energy balance and/or self-sufficiency. Most of the studies take self-sufficiency in literal or absolute terms, aiming to prove that a certain combination of energy production and storage can meet demand in a particular context and time period.

Solar PV as a technology has gained the most interest in the energy autonomy literature (see Fig. 4). Due to the intermittent nature of solar production, it is typically combined with other technologies (see Table 2) and the configurational analysis showed that the most frequently analyzed combination was solar PV, wind energy, and electric storage. Overall, seven system combinations were scrutinized more than once in the existing literature, as listed in Table 2. Systems featuring multiple technologies dominated the studies, with only 14% of studies examining systems with a single technology. Even though the list of single technologies covered in the studies is rather extensive, solar PV is the only technology that was repeatedly analyzed as a single technology solution. Overall, from the technology selection standpoint, studies seemed to aim to find a unique combination of technologies—that is to say, typically any given combination can be found only once in the literature.

As the configurations in Table 2 demonstrate, there is significant interest in using solar PV in combination with wind energy. As both are intermittent energy sources, energy storage is needed to achieve self-sufficiency at the system level. Solar PV can also be combined alone with electrical storage, which is the second most popular combination in the studies. Biomass or diesel to support intermittent generation—either alone or in combination with storage technology—has often been reported in studies.

In general, all renewable energy technology types are present in the literature and are part of the methods implemented in the pursuit of energy autonomy. Different types of storage systems too are used in experiments, simulations, and scenarios, including heat storage [30], hydrogen storage [68], fuel cells [69], and natural gas geological storage [36] (Fig. 5.). In terms of carbon dioxide (CO_2) emission considerations, geological storage for CO_2 is sometimes included in scenarios [36]. Renewable hybrid systems attract the most interest, but renewable systems supported by fossil fuels can also be simulated, including wind–diesel–battery hybrid systems [51] or geothermal energy with coal combustion and different types of storage [36]. Rarer hybrids include biomass fermentation, biogas-to-energy combined heat and power (CHP), and waste incineration [5].

3.6. Time spans

The review found that studies on energy autonomy have much less focus on the theme time, and do not have clearly set time periods within which energy autonomy should be achieved by. A distinction can be made between 'net energy autonomy', which is balanced over the space of a year, and 'complete energy autonomy' over the year. The latter one implies an off-grid operation [30]. Particularly in studies concerning energy storage and its viability, time period of autonomy can range from a single day to a year [70].

Simulations of self-sufficiency are usually based on historical consumption data, and estimated power generation and storage in certain conditions. However, demand supply management is rarely taken into account in the studies. Brosig and Waffenschmidt's study on households is an exception and includes demand shifting and the prioritization of different loads [23]. In many of the studies, a microgrid is often assumed to be present between production and consumption nodes. Menconi et al. [13], for example, studied district heating as a solution for heat distribution in achieving energy autonomy in residential buildings.

3.7. The economic dimension

In terms of considerations for economic aspects of energy autonomy, the review found that more than 30 studies [e.g. Refs. [34,40,49,54,71], considered it on some level, making it a prevalent theme in these studies. Although the economic feasibility of technical systems able to provide energy autonomy is widely discussed in the literature, studies rarely provide an exact economic analysis. There are, however, exceptions, and certain studies have included, for example, the cost of energy, grid costs, and investment analyses. For example, Ye and Huang's [39] study on Taiwan includes an economic evaluation of investment in solar energy with a cash flow analysis. Kaldellis and Kavadias [49] provide a detailed energy production cost analysis of the Aegean archipelago.

The cost of energy is an often-mentioned issue in relation to competitiveness. In economic terms, energy autonomy seems to be about convincing different stakeholders (e.g., authorities, policy makers, corporations, financiers, consumers) that setting up an energy autonomous area with renewable energy and storage systems can also be an economically viable solution. The reviewed articles underscore though that energy autonomy implies economic considerations and that full-scale implementation would require further economic analysis [48]. A view that is far less prevalent is the idea and value of constant energy

[4] "Other" includes reticulated liquid petroleum gas, coal combustion, biomass fermentation, district heating, waste incineration, passive solar design, carbon capture and storage, zero energy buildings (ZEB), energy demand control, and water electrolyzers.

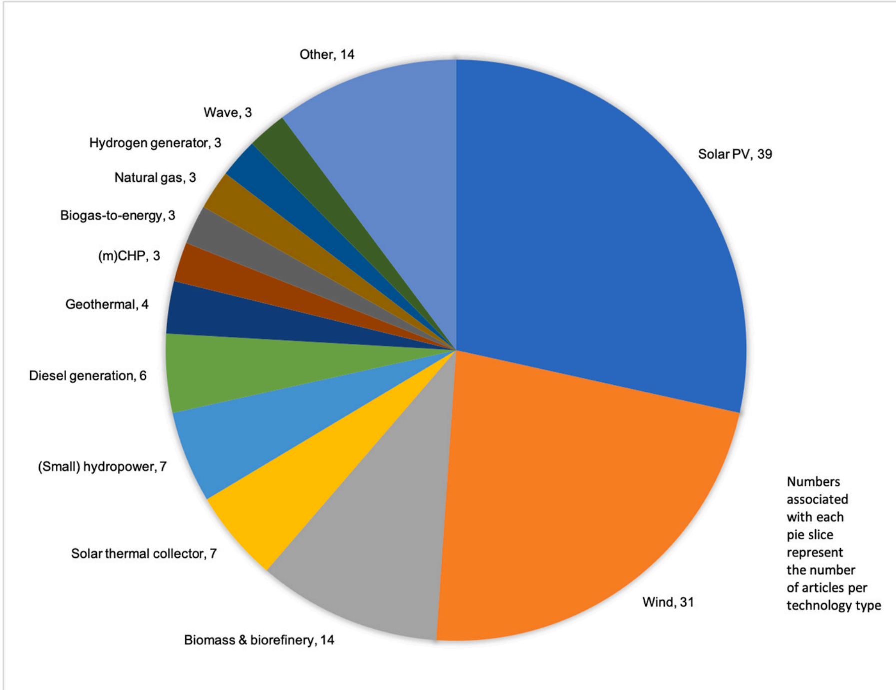

Fig. 4. Number of Articles per generation technology 2000–2018.[4]

Table 2
Results of the configurational analysis.

Intermittent energy sources		Incineration-based generation	Storage	Number of cases (/papers)	Reference numbers
Solar PV	Wind		Electrical storage	5	[33,40,47,50,62]
Solar PV			Electrical storage	4	[3,31,34,49]
	Wind	Pumped hydro		3	[36,42,54]
Solar PV				3	[63–65]
Solar PV	Wind	Biomass		3	[44,55,66]
	Wind	Diesel	Electrical storage	2	[46,67]
Solar PV	Wind	Diesel	Electrical storage	2	[5,39]

costs, which energy autonomy may entail [41]. When an area seeks energy autonomy, or becomes autonomous by owning renewable energy (bioenergy excluded) generating assets, the cost of energy is—maintenance aside—based on a predetermined fixed investment cost over the life cycle. In other words, the cost of energy output is fixed during the life cycle, enabling local owners to see reduced energy costs as a valuable feature of energy autonomy.

Grid parity, where the local cost of local generation is the same as that with an external energy supply, has been proposed as a strong reason to aim for energy autonomy. Rapid cost reductions in certain renewable energy generating technologies (decreasing levelized cost of electricity [LCOE]), such as solar PV, can mean that the local LCOE lies below the current electricity price for households in some markets. This means that in an economic sense it is best for households to use all their self-generated power locally without exporting it to the grid. This, however, does not mean that a household can create a lower-LCOE, off-grid solution that works in an autonomous manner full time and all year around. As shown in Section 3.5 on technologies, for the case of solar PV and energy autonomy, there is less balance, and storage becomes essential. The smaller the unit (e.g., a household) is, the less balance there is between demand and supply, and consequently there is an increased need for battery solutions. Electrical storage is still expensive, and regardless of the scale of deployment—be it household, community, or municipality—full self-sufficiency is not always viable [6].

Greater energy autonomy can lead to more decentralized energy systems, which consequently can lead to lower transmission costs, lower central generation capabilities, and lower regulating power needs. In these systems, network loads go down when more heat or power is generated and used in the same location, which in turn can preclude costly transmission network expansion [6].

Energy autonomy also concerns sharing economic benefits and costs fairly among stakeholders. Ownership is an integral part of the economic design for renewable energy projects; it can both promote and undermine civic energy autonomy. It creates a control point, which defines, for example, who reaps financial benefits from the technology and who can make future decisions about the usage of that technology.

Energy production inherently requires manual work and has employment implications. In addition, energy autonomy in a particular geographical area may generate pressure to move energy production related jobs to that area. This can consequently have an impact on local job creation and employment. Job creation is seen as one of the benefits that greater energy autonomy can bring [41,72]. Particularly in rural areas that face a population exodus, this has been a very important aspect that increases the vitality of the area and brings new employment opportunities when traditional rural jobs are under pressure [63].

Katsaprakakis and Voumvoulakis [55] highlight tensions between national and local benefits of renewable energy projects. National policies and politics favoring the national economy may influence, for example, siting decisions of wind farms. When the most optimal local areas for wind power, such as mountains and hills, are occupied by large, national energy investors, benefits for local communities can simply be lost.

Community energy and grassroots activism have familiarized people with alternative economic models [73]. There is, however, little evidence of a general change toward greater equity or achieving an energy system that is significantly more just than the current system. In many

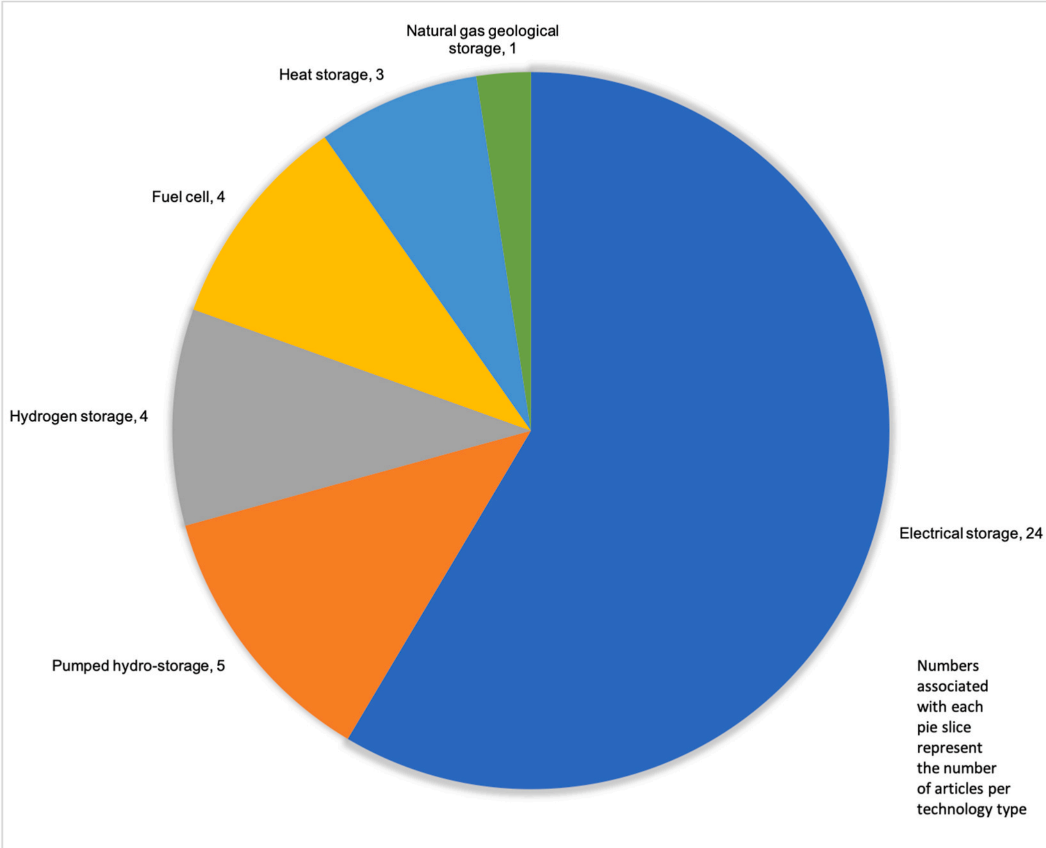

Fig. 5. Number of articles per storage technology 2000–2018.

cases, renewable energy deployment and even smaller-scale grassroots approaches, such as community renewable energy projects, are enveloped by the dominant capitalist economic system, and its concepts of growth, ownership, and notions of value and profit [74].

3.8. The social dimension

In addition to economic and environmental impacts, the review found that energy autonomy can deliver a host of social impacts [2]. While the social dimension of energy autonomy is widely recognized in the literature, it is nevertheless only sporadically presented and rarely systematically addressed. The social dimension of energy autonomy can be understood in very generic terms as a concept in which an energy system has positive "social impacts" when simply, for example, supplying electricity to people [35]. Similarly, Miller and Buys [31] define the social dimension of energy autonomy in a residential housing context as covering "thermal comfort" and "universal design".

A number of articles do, however, explain in detail what the social aspects of energy autonomy may entail. Maes et al. [32], p. 2002] present a rather comprehensive list of social feasibility factors to be considered when building an energy autonomous neighborhood. These include "trust, openness, clarity between parties, reciprocal relations, enthusiasm and experience of initiators and supportive actors or facilitators, perception about other feasibility factors, mentality of cooperative thinking (live and let live), influence on companies' image, experience with interfirm clustering, win situation for stakeholders politic & social support (policy, NIMBY effects)". Some of these social factors point toward a concept of energy democracy—that is, an energy system that seeks to be democratic in the sense that decisions are made by the users of energy [75] to advance social justice needs of communities [76].

Attempting to achieve energy autonomy in urban areas may pose additional challenges. Spatial planners have to identify an appropriate level of development intensity, which requires the consideration of environmental and social issues [39]. Furthermore, energy harvesting and optimization in urban and residential areas has direct impacts on the land use of an area, which may lead to the degradation of the local landscape's aesthetics and how people enjoy their everyday environment [56].

Although different modes of energy generation can lead to very different costs and benefits in social, economic, and environmental dimensions, the analysis of different technological solutions, sustainability goals *and* sustainability impacts together is very uncommon in the literature. Tragopaulos et al. [56], however, provide three different scenarios that optimize different aspects of the solution with regard to energy autonomy: maximization of the energy harvest, social impact (social sustainability), and the financial viability of the solution (cost efficiency).

4. Discussion

In the above sections we have reported the findings from a systematic review of energy autonomy, based on 71 peer-reviewed academic articles from 2000 to 2018. The review found that energy autonomy research comprises six distinct themes: 1) scale, 2) motivations, 3) technologies, 4) time span, and 5) economic and 6) social aspects. In the following we discuss why energy autonomy matters, what are the policy implications of our study, and how future research could further examine energy autonomy.

4.1. Why energy autonomy matters—Enabling better energy democracy

In general, while there are several, diverse motivations driving the quest for energy autonomy—including independence from energy markets and utilities, stability with regard to fluctuating energy prices or transmission costs, environmental concerns, and a desire for better energy security—the review found that these are not explored often in the literature. While it is widely recognized in the literature that energy autonomy can lead to increased tax revenues at the municipal or national level, a much less discussed aspect has been how local energy autonomy could enable better engagement by end users and communities in energy decisions. Initiatives such as local community energy projects have not yet been able to break into mainstream energy systems and thus one motivating factor for aiming for energy autonomy could be the development of a more democratic energy system. This has been exemplified by citizen-led energy initiatives in Germany for example, which have shown an increased level of participation and energy democracy. Energy autonomy could therefore allow active citizen participation in energy systems, enabling both citizen-led energy production and consumption, often termed as "prosumption" [77–79]. Greater autonomy also enables users, if they wish, to take part in a wider set of activities inside the value chain in comparison to centralized generation. Energy autonomy can thus enable civil society actors to participate in decisions regarding technology choices, expansion, and financing.

Local energy system ownership by end users and citizens could also provide better energy security by enabling individual users to fully control energy production. An important aspect of control is an inbuilt incentive to develop energy provision and further invest in the system if needed. When energy users own the production equipment, they also know the cost of producing energy for the whole life cycle of the production unit, including potential maintenance.

Active user engagement with micro- and small-scale energy generation technology can also involve technology configuration to meet local requirements. Without ownership of the production unit, the user is usually forbidden from making technological modifications and configuration changes. This leaves the homeowner's role relatively passive and vague in terms of energy production. In comparison, an active user adaptation of technology (e.g., building do-it-yourself (DIY) projects, creative appropriation, and the creation of user innovations), would mean that both ownership *and* control of the system stay with the user (e.g., a household).

4.2. Policy implications

In the current economic climate, where greater economic and social inequalities are emerging and serious problems such as energy poverty [80] and access to energy [81] are persisting, researchers and policy makers ought to pay more attention to energy autonomy.

Earlier studies have shown that dominant financial institutions are crucial in shaping the ownership structures and technology choices of energy systems and futures [82,83]. Thus, energy policy can play a crucial role in creating protected spaces for local energy autonomy by using local renewable energy sources. In the different stages of a technology's diffusion in a market, the models of ownership go through transformations. Particularly at the beginning of the acceleration phase of an energy transition [84], different forms of local citizen participation and citizen financing may advance the uptake and social acceptability of projects [85]. Later, in a more mature market situation, diverse ownership structures can support the realization of democratic decision-making concerning technology deployment models.

A successful energy policy creates an environment that supports the creation of new socio-technical deployment alternatives that can provide a superior, sustainable alternative to "business as usual" [86]. Local and national governments can develop new types of mechanisms. Policy mechanisms vary depending on at which scale energy autonomy is being pursued. In regional-level specific planning, for example, rules that assist renewable energy can be used (cf. Samsø) [87]; municipalities can for instance mandate the use of renewable energy in their public buildings (cf. Güssing) or set specific renewable energy generation targets [88]. At the household scale, the reduction of transaction costs, risks, and uncertainty can enhance consumer interest in building host-owned, self-sufficient systems [89]. These policy mechanisms can include administrative processes with regard to grid connection, or subvention schemes such as feed-in-tariffs. The literature also highlights the role of finance. Financing offered by banks or other financial institutions directly, or via equipment vendors, can be developed to remove the need for up-front payment when deploying local energy generation. Francisco DeVries gives an example of this type of an approach in California where municipalities participate in providing financing for low-income consumers by issuing bonds,[5] and whose proceeds finance the up-front costs of PV systems [90]. The initial cost is paid back by participating homeowners paying the tax assessment costs with the money they save on utility bills. Unlike with third-party financing, under this model the ownership of the energy production unit remains with the building owner from the outset [91,92].

4.3. Avenues for further research

The review found that most studies in energy autonomy have been typically based on a single case study and many of these have been simulations. There is thus space to expand the methodological range of energy autonomy research. Development of the field would benefit from examining multiple case studies, using both qualitative and quantitative methods and different real-life cases. Furthermore, very few attempts [6] have been made in the area of testing theory deductive work on energy autonomy.[6]

Another, rather overlooked area in the literature on energy autonomy is how local energy autonomy is built in households and how new types of socio-technical arrangements are constructed. Distributed generation with small-scale renewable energy technologies is scaling up in the marketplace. Together with new technologies, new business models are emerging that change the roles of the actors, and these typically have an impact on how ownership is organized, and how financial benefits and liabilities are shared.

This review found that the literature examining energy autonomy is dominated by an approach that highlights solutions, but is less forthcoming with the potential drawbacks of energy autonomy, especially in terms of social aspects [66]. In practice, and perhaps in its worst case, energy autonomy might lead to higher energy system costs and could thus cause public protest and social reluctance. Simulations of energy autonomy have typically been system wide, and have taken into account at least some system-wide implications within the specified geographical area. Systemic thinking with regard to implications has, however, often been overlooked especially factors going beyond the energy system. In other words, there is limited analysis of what complications and/or injustices for example regional energy autonomy may create [24] in local areas, or even in other parts of the world. Thus, further research could benefit from examining energy autonomy together with energy justice and a whole systems approach [93,94].

Finally, the philosophical foundations of energy autonomy are still rarely unpacked, challenged or critically examined. A simple technical examination of self-sufficiency and/or energy autonomy could lead to objectives where regional isolation is the aim. As a multidimensional concept with separable components, energy autonomy, however, goes beyond this. Energy autonomy should not be considered as leading to system optimization in closed areas, as this may not advance sustainability in the most effective manner and could even lead to geopolitical conflict. Smart regulation, and organizational and operational designs that nudge the practices of consumers [95], may lead to approaches that better foster the objectives of energy autonomy without artificially

[5] In the US these are called Property Assessed Clean Energy (PACE) bonds.

[6] Deductive hypothesis testing studies have been conducted at the individual user level, for example to test linkages between social acceptability issues and energy autonomy.

limiting physical areas and/or closing off interaction with others.

5. Conclusions

This study shows that energy autonomy can provide a useful lens as the move toward net-zero societies takes place. Few exceptions aside, much of the literature sees energy autonomy as a normative outcome that fosters self-sufficiency with social and environmental sustainability goals, in an economically viable way. As energy autonomy is built on various dimensions and targets, it can be hard to asses it with one figure or a numeric sum. Degrees of energy autonomy vary, and different aspects of energy autonomy can be valued in different ways depending on context. The economic sustainability of autonomous energy systems is, however, often challenged and simulations are therefore conducted to prove that energy autonomous systems could also be economically viable. There can certainly be tradeoffs—creating a self-sufficient energy system where local supply can meet local demand in the short and long term, and in a socially equitable and economically viable way, can be very challenging. Typically, such trade-offs occur between the level of self-sufficiency and economic factors.

Economic and social aspects are interlinked as ownership creates a control point for the technology and is a crucial component in the socio-technical evaluation of an energy system [90]. Via local ownership, households and/or communities can have power over their own energy supply, which may prove self-determining. They can construct their own goals and values, and decide and plan for future actions in order to achieve personal or community goals that are in line with those values [96,97].

Based on the scrutinized literature and taking into account the diverse set of factors surrounding the concept, energy autonomy can be defined as *a concept of local energy generation and use, providing a self-sufficient power balance between demand and supply, in a desired time span and with the ability for stakeholders to self-determine energy provision in a sustainable, economically viable, and socially equitable way*.

Further examination of energy autonomy can ensure that future energy systems are designed so that they foster self-sufficiency with openness, share costs equally, and go beyond a technology-only focus to include the multidimensional aspects that energy autonomy entails.

Declaration of competing interest

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

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