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The double-edged sword of decentralized energy autonomy

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ABSTRACT

Whilst there are clear advantages to decentralized energy systems, one main disadvantage is their lack of economic scale effects. The development of decentralized energy systems goes hand in hand with a trend towards community energy. Many of these communities claim energy autonomy as their main motivation for investing in local renewable energies. They define energy autonomy as generation exceeding demand on an annual basis and are therefore less autonomous than without these technologies. Communities that strive for this ideal utilize the electricity network infrastructure more than traditional end of the pipe consumers. At the same time, they make a much lower contribution to the costs of this infrastructure, currently charged per unit of energy used, and often benefit from subsidized renewable energy technologies. Hence this motivation is at best questionable and at worst misplaced. A continuation of the recent rapid reductions in battery prices expected by many experts, however, could make the economic case for truly energy-autonomous municipalities. This clearly raises important questions for researchers and policymakers alike. For example, in which sorts of municipalities could such solutions make sense and what are the consequences for the overarching, mainly centralized energy system?

1. Small is beautiful?

The characteristics of renewable energy resources mean that much of their installed capacity is decentralized. Of the 40 GW and over 1 million photovoltaic (PV) plants installed in Germany, around 98% are connected to the low voltage distribution networks (Wirth, 2016). On the supply side, buildings account for about 40% and 36% of the total European end energy consumption and greenhouse gas (GHG) emissions respectively (De Groote and Rapf, 2015). Most of this energy is employed for space heating and hot water, which is mostly (currently around 87%) generated in or near to the building it supplies (Connolly et al., 2013). So-called *community energy* involves mainly private individuals and farmers investing in and operating low carbon technologies (LCT), such as micro-CHP and heat pumps, PV, batteries and insulation measures (OECD/IEA, 2011). One of the main motivations for community energy is so-called energy autonomy, but this is mostly defined on an annual timescale and refers solely to electricity. But the characteristics of heat and electricity systems mean that decisions made at building and municipality scales have strong interactions. Hence the distinct national, regional and local levels of energy-political influence have in some cases resulted in incongruities (Bauknecht et al., 2015).

2. (De-)Centralization

Ackermann et al. (2001) refer to distributed generation[1] as being connected on the customer side of the meter. Whereas decentralized technologies are mainly connected to the distribution network, centralized ones are mostly connected to the transmission network. Hence the capacity of one single power plant in a distribution network is typically (much) lower than 100 MW_{el} (Funcke and Bauknecht, 2016). As shown in Table 1, the centralized system is characterised by a linear structure, with a small(er) number of (much) larger power plants and a mostly linear flow of electricity from generation through transmission and distribution to the demand side. In contrast to this, the decentralized energy system is characterised by a (much) larger number of (much) smaller power plants and owners/operators. The system is more integrated, both vertically from supply through to demand and horizontally between different energy vectors such as power, heat and gas. Whereas the rate of connection to the electricity transmission and distribution systems is extensive in Europe (mostly 100%, World Bank 2016), heat is not typically transported over large distances. So economies of scale motivate an increasing aggregation for the electricity system, whereas decentralized energy systems can avoid costly transmission network expansion and centralized generation capacity.

Integrating renewable energies requires a combination of measures, for example network expansion/strengthening, increased flexibility, storage, sector coupling and intelligent control systems. Flexibility in a centralized system is typically connected to the transmission network and balanced over large geographical areas, with demand side management (DSM) offered by large (e.g. industrial) consumers. Storage is

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[1] The terms distributed and decentralized generation are employed synonymously here.

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Table 1
Characteristics of centralized and decentralized energy systems (own illustration based on Funcke and Bauknecht (2016), Bauknecht et al. (2015), Jensch (1989), Weber and Vogel (2005)).

Characteristic(s)	Centralized energy systems	Decentralized energy systems
Structure	Linear: generation, transmission/distribution, demand	Integrated: ● Vertically, between voltage levels ● Horizontally, between energy carriers
Number of power plants	Few large(r) plants	Many small(er) plants and prosumers
Ownership/actors[a]	Few large(r) companies	Many small(er) owners, e.g. private individuals, farmers
Data: amount	Moderate	Very large
Concentration of supply security[b]	High	Low
Investment decision: flexibility and speed	Low	High
Controllability: markets	Centralized, increasingly integrated	Centralized and/or decentralized
Controllability: location	Generation, transmission and distribution	All areas of system, i.e. including demand
Smoothing effect through aggregation	High	Low
Economic benefits	● Economies of scale in large plants ● Lower distribution grid investment	● Lower transmission grid investment ● Lower centralized generation capacities and regulating power needs
Flexibility: amount	Roughly the same for both systems	
Flexibility: characteristics	● In transmission grid ● Larger geographical areas ● Load management from large consumers	● In distribution grid ● Smaller geographical areas ● Load management from small consumers ● Higher ICT requirements ● More sector coupling
Storage requirements: amount	Roughly the same for both systems	
Storage requirements: characteristics	Large, centralized	Small, decentralized
Relevance of social acceptance	Less important	Very important

[a] Note that a large number of actors would also be possible in a centralized system, but currently this is not the case.
[b] This refers to the impact on the energy system in the event that the average-sized power plant fails.

also generally large scale, such as pumped hydro, and the connection of large regions might also by realized through a "supergrid" approach with long distance High Voltage Direct Current (HVDC) cables. In decentralized systems on the other hand, the flexibility is connected to the distribution grid and covers much smaller geographical areas; storage units and DSM consumers are also much smaller (Funcke and Bauknecht, 2016). The management of this flexibility is expected to require more Information and Communication Technology (ICT) than in the centralized case, due to the much larger number of plants and actors within the system.

Centralized energy systems are controlled through centralized markets that are becoming more geographically integrated, whilst the necessity for decentralized markets is currently being discussed e.g. in the "Smart Energy Showcases - Digital Agenda for the Energy Transition" (SINTEG) projects (BMWi 2017). The provision of balancing power within decentralized energy systems typically requires a pooling of power plants into Virtual Power Plants (VPPs) in order to meet the minimum bid requirements in these markets. In the extreme, the Blockchain technology could enable peer-to-peer trading between prosumers[2] and ultimately obviate the need for marketplaces altogether (dena, 2016).

Jensch (1989) seems to be the first to coin the term "degree of centralization" (*Zentralisierungsgrad*), which raises the question about the level at which decentralized energy systems should be aggregated and balanced (Bauknecht et al., 2015). Currently, most autonomous regions (next section) rely on the overarching centralized energy system for their flexibility and controllability (Funcke and Bauknecht, 2016). For example, Wimmer et al. (2014) compare centralized with decentralized wind expansion scenarios, concluding that the overall flexibility requirements are similar in both cases. Reiner Lemoine Institut (2013) finds that a decentralized renewables expansion would be economically favourable, largely due to higher required network expansion costs in the centralized case. Others reach the opposite conclusion, however, that centralized and hybrid energy systems are more economically efficient than purely decentralized ones (Acatech, 2016). Although it is clear that a completely renewable energy supply based on decentralized, autonomous regions does not seem economical due to very large storage requirements (Peter, 2013), there is no clear consensus about the optimal degree of centralization.

[2] Producers and consumers of energy, typically electricity.

3. Communal and autonomous?

The importance of social acceptance is another distinguishing characteristic of decentralized energy systems. In this context, community energy (Walker, 2008; Walker et al., 2010) has been particularly strong in Germany, where around 46% of renewable energy capacity is owned by private individuals and farmers (Klaus Novy Institut e.V. and trend:research, 2011). Often these projects involve energy cooperatives, of which 718 have been founded since 2006 (DGRV 2014), and/or buying the local energy (electricity and gas) distribution infrastructure back from the local utility. Community energy systems are characterised by an involvement along the energy value chain; those involved in the project should also reap the benefits (Rae and Bradley, 2012). But community ownership is not always advantageous, and local ownership should not be equated with local benefits (Bain, 2011). Community energy can stimulate the local economy, but the net effects are very difficult to measure and depend very much on the local conditions. In addition, there are also negative effects such as job displacement in other sectors, which must also be considered.

Another common theme is the presence of key stakeholders (Walker, 2008, Wirth 2016), who should have the required expert knowledge and connections to and within the community. But also the regional identity and a sense of belonging are important prerequisites and/or consequences of community energy projects (Müller et al., 2011). This identity also results in a 'community spirit' (Wirth, 2016, Rogers et al., 2008), which along with interpersonal trust and collaboration (Walker et al., 2010) are also necessary but not sufficient prerequisites for successful projects.

One common motivation for community energy is the wish to be more independent from central markets (Boon, 2014). The willingness to pay for locally generated electricity is higher than for imported electricity, but much of this 'local green electricity' comes from Scandinavian or Austrian hydropower plants (McKenna et al., 2015). This desire for more energy autonomy (Deuschle et al., 2016; Rae and Bradley, 2012; McKenna et al., 2014, 2015, 2016), also called energy autarky (Müller et al., 2011) and self-sufficiency (Deuschle et al., 2016;

Balcombe et al., 2015), has many motivating stimuli (Engelken et al., 2016) but is the main motive for community energy (e.g. Volz, 2012). Yet in Germany the security of supply, at 16 min per customer per year as measured by the SAIDI[3] index, is one of the highest (i.e. the shortest index duration) in Europe (BMWi 2014). The law of large numbers means that stochastic components of load and renewable generation profiles are partially or wholly cancelled out when aggregated. This was recently achieved by aggregating and providing German balancing power over larger areas (Hirth and Ziegenhagen, 2015), which actually tends to encourage a higher level of interconnection.

4. The need for a framework

A review of community-scale energy autonomy in Germany, Austria, and Switzerland highlights examples such as the 100% Renewable Energy regions (total 140 regions in 2014) and the Bioenergy Villages (around 140) in Germany, the 'klima: aktiv' regions (at least 46) in Austria and the Energy Regions (at least 40) in Switzerland (McKenna et al., 2014). Austria is the only one of the three countries with clear energy-political ambitions and support for energy autonomous regions, in the context of the 'klima: aktiv' programme. This accounts for the relatively high number of communities involved: in 2014, 9 communities were showing very good progress and a further 37 good progress (BMLFUW 2014a). Noteworthy thereby are the two municipalities of Mureck and Güssing (BMLFUW 2014b), both of which originally had energy autonomy objectives. In addition, there are specific energy autonomy goals in the municipality of Murau (Energievision Murau, 2014) and the Federal State of Vorarlberg (Amt der Vorarlberger Landesregierung, 2010). In Germany, the village of Jühnde[4] was the first Bioenergy Village (Heck et al., 2014) and Feldheim[5] is widely recognised as a pioneer project in energy autonomy (Backofen, 2011). In Switzerland the communities of Toggenburg, Goms und Val-de-Ruz all have energy autonomy as a goal (Eichenberger et al., 2011). Some but not all of these villages have websites, as referred to in the footnotes, or may be found within the broad overview of initiatives around the world given on the 'Go 100% Renewable Energy' website.[6]

Several authors have carried out scientific research into some of these typically smaller, rural municipalities. The majority of the examples employ the first definition of energy autonomy given below; only a few have an explicit objective to achieve an annual energy balance. Examples include Schmidt et al. (2012), Jenssen et al. (2014) and Burgess et al. (2012). Schmidt et al. (2012) examine the agriculturally dominated rural region of Sauwald in Upper Austria, with 21,000 inhabitants, with optimization and land use models. Jenssen et al. (2010) give an overview of experiences and lessons learned so far in the so called Bioenergy Villages in Germany, based on methods of LCA, exergy allocation, as well as CO_2, cost and energy balances. They contrast the advantage of reduced local CO_2 emissions with the disadvantages of increased costs and competing land use (e.g. for food). Burgess et al. (2012) present a case study of an Marsten Vale (16,000 ha) in southern England, UK, with land-use mapping approaches, interestingly considering food and material use next to energy, and therefore the land use competition relating to these uses.

Despite the large number of international examples of energy autonomy projects, both related terminology and assessment methods suffer from a lack of formalization and consistency. This includes the terms employed to describe the concept (see above) and the ways in which it is defined and measured. Several complex aspects should be considered when assessing such systems, not least of which are the types of energy, applications and sectors. A working definition for energy autonomy has been proposed (McKenna et al., 2015), which distinguishes between a *tendency through decentralization* (1), *an annual balance* (2) and a *completely off grid solution* (3). In practice, most community energy employs the second definition and refers only to electricity, which emplies ceteris paribus a stronger, bidirectional interaction with the overarching energy instructure than beforehand. But beyond this rudimentary distinction there is a requirement to develop a robust and consistent methodological framework within which to better understand these initiatives.

5. The double-edged sword

Grid parity provides an especially strong motivation for higher energy autonomy at the local level. The rapid reductions in the generation costs (Levelized Costs of Electricity, LCOEs) of PV mean the generation cost (currently around 12 €ct/kWh in Germany) lies below the electricity price for households in many countries (around 30 €ct/kWh) (cf. Fig. 1). Hence as long as the power demand exceeds the PV generation, it makes economic sense to use this power within the household rather than export it to the grid.

Without an electric battery and behavioural interventions, the scope for utilizing this self-generated electricity within the household is constrained to about 20–40% (Luthander et al., 2015). The self-consumption can be increased through different system orientations at the municipal level (Killinger et al., 2015). But at the building level these options have a quite small impact (Weniger et al., 2013), and increasing self-sufficiency is most attractive in higher demand buildings (Balcombe et al., 2015). There are clear economic scale effects related to energy autonomy in residential buildings (McKenna et al., 2016), but at the time of writing a fully autonomous municipal-level electricity supply is not yet economical. If battery prices reduce in the coming years as quickly as some experts believe, this situation could change just as rapidly (Nykvist and Nilsson, 2015).

If communities increase their degree of local energy autonomy, they thereby reduce their imports from medium and high voltage electricity networks. Hence they contribute less to the overall network costs, which are charged as a surcharge for all end-consumers (with some exceptions) per unit of electricity purchased. In addition, they may benefit from subsidies for their renewable electricity. But the total costs of network fees and subsides are shared by all consumers (again, with exceptions). The marginal effect of one project is clearly small, but thousands of autonomous municipalities could incur substantial additional costs for consumers (Jägemann et al., 2013). Despite the clear microeconomic benefits to consumers from increased levels of electrical autonomy, the net macroeconomic effect could be detrimental.

Partly (definition 2) or wholly (3) autonomous decentralized energy systems therefore present significant energy policy and research challenges. Firstly, the link between energy autonomy and community energy should be further explored. Secondly, whilst working definitions for energy autonomy have already been proposed, these should be further refined and validated through application to additional cases. Thirdly, assessment methods and indicators are needed to assess energy autonomy according to technical, economic and environmental criteria at various levels of aggregation, from buildings to whole regions (some examples are given in Schreiber, 2012). An example of a new indicator might be the fraction and distribution of the time that an energy system is autonomous (according to definition 3), as this has important implications for the associated integration costs (Ueckerdt et al., 2013). These indicators should be applied to diverse municipalities to assess their suitability for energy autonomy, and the interactions between different types of community energy systems analysed. This would help to answer the question about the 'optimum degree of centralization'. Finally, the effects that thousands of partly or wholly autonomous municipalities or regions could have on the overarching energy system should be analysed. All of these research fields should be explored in order to underpin informed policymaking for (partly) autonomous decentralized energy systems.

[3] System Average Interruption Duration Index.
[4] http://www.bioenergiedorf.de/en/home.html, checked 15.11.17.
[5] http://nef-feldheim.info/?lang=en, checked 15.11.17.
[6] http://www.go100%.org/cms/index.php?id=19, checked 15.11.17.

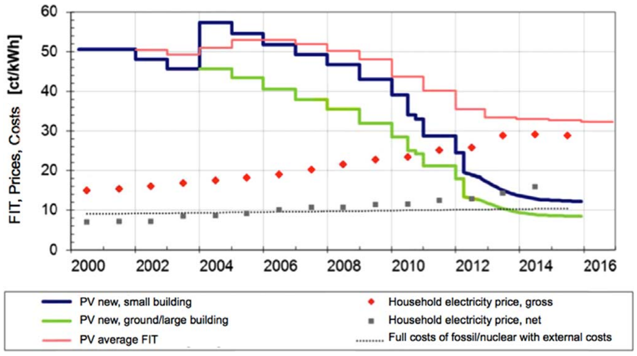

Fig. 1. Recent developments in PV generation costs and household electricity prices in Germany (FIT: Feed-in Tariff, source: Fraunhofer ISE 2015).

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