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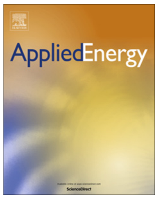

Energy autonomy in residential buildings: A techno-economic model-based analysis of the scale effects

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HIGHLIGHTS

- Energy autonomy (EA) in residential buildings is incentivized.
- Focus on the scale effects on economics of EA.
- Shift in economic optimum from 30% to 100% EA with scale.
- Complete EA only economical above 560 households.
- Further work should analyze system effects.

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ABSTRACT

An increasingly decentralized energy supply structure alongside economic incentives for increasing the level of self-generation and -consumption are encouraging (higher levels of) energy autonomy. Previous work in this area has focused on the technical and economic aspects of energy autonomy at distinct scales, from individual buildings, through neighborhoods to districts. This paper employs a mixed integer linear program (MILP) to assess the effects of aggregation across these scales on the economics of energy autonomy in residential buildings. The model minimizes total energy system costs over the lifetime of the energy system, including micro-combined heat and power (mCHP), photovoltaic (PV), thermal and electrical storage, and boilers, at five distinct scales and for nine demand cases. It is subject to several constraints, among other things the degree of electrical self-sufficiency. The results indicate a shift in the economically optimal level of electrical self-sufficiency with scale, which in Single-Family Houses (SFHs) means from around 30% at the individual building level to almost 100% in districts of 1000 SFH households. Above around 560 households it could be economically advantageous to make a district of residential buildings electrically self-sufficient. In addition, a marginal increase in electrical self-sufficiency is significantly more expensive at lower aggregation scales (i.e. single buildings) compared to the scale of neighborhoods and districts. The level of interaction with the electrical distribution network increases with increasing electrical self-sufficiency before then decreasing at very high (above 70%) levels. Future work should focus on a richer socioeconomic differentiation, considering other sectors and technologies, incorporating demand side options and analyzing the effects on the overarching energy system.

1. Introduction

Buildings and urban areas have attracted much attention in the context of decarbonizing the energy system due to their large proportion of the global energy demand and the increasing proportion of the population living in them [1]. On the one hand there is a large potential for energy efficiency improvements on the demand side. This means the refurbishment of existing, and higher standards in new buildings, whereby the greatest challenge lies in the former area due to their sheer number [2]. On the other hand, renewable and highly efficient energy sources promises to meet the remaining demand with low or zero carbon energy supply.

Partly due to the low energy density and highly distributed nature of renewable energy sources, much of their utilization has been decentralized, e.g. photovoltaic (PV) on buildings, biomass and wind plants within or near to municipalities. The majority of these

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Nomenclature

Abbreviation	Description
B	biomass
BOI	boiler
BS	battery storage
CAP	capacity
CHP	combined heat and power
$\mathrm{DA_{el}}$	degree of electrical autonomy
DEM	demand
DHW	domestic hot water
DIR	direct
DSM	demand side management
$\mathrm{DSS_{el}}$	degree of electrical self-sufficiency
E	external
EL	electricity
FIX	fixed (cost)
GII	grid interaction index
HP	heat pump
I	internal
INV	investment (cost)
LCA	life cycle assessment
LCOE	levelized costs of electricity generation
mCHP	micro-combined heat and power
MFH	multi-family house
MILP	mixed integer linear program
Norm	normalized
nZEB	near-Zero Energy Building
PV	photovoltaics
RE	renewable energy
REF	reference
REV	revenue
$\mathrm{SCR_{el}}$	self-consumption rate for electricity
SFH	single-family house
SH	space heating
ST	solar thermal
STG	storage
TS	thermal storage
VAR	variable (cost)
W	wind turbine(s)
ZEB	Zero Energy Building

plants in Germany are owned and operated by private individuals, including farmers and communities [3]. Especially if located in or near a demand centre, an expansion of existing renewable energy capacity thus leads, ceteris paribus, to a higher level of local energy autonomy, which is generally defined here as that fraction of the local electricity demand met by local generation (see Section 3 for precise definitions).[1] The distinction is thereby made between net energy autonomy, i.e. balanced over the year, and complete energy autonomy, which implies an off-grid operation.

Some of the motivations for community energy projects that tend to increase the level of energy autonomy include greater independence from centralized energy markets (and their price fluctuations), relief of and/or independence from[2] the local electrical transport and distribution networks (and thus lower network fees for the community), more control over local decisions relating to the energy system and a locally-sourced, low carbon energy supply [5–7].

Generally the adoption of renewable energies has relied on political support in the form of quota systems and feed-in tariffs, although others such as investment grants and tax exemptions do exist. For PV this was until quite recently the case, but now this technology has reached grid parity in several countries [8]. This means that the generation costs, expressed as the levelized costs of electricity generation (LCOE), are at or below the electricity price for the end consumer. The discrepancy between electricity generation and residential demand profiles, however, makes increasing the fraction of self-consumed electricity in the absence of an electrical storage system quite challenging. Hence there has been renewed interest in battery storage devices for small-scale, decentralized domestic applications.

Some key research questions arise from this current situation, in which there are motivations for increasing energy autonomy at the individual building, neighborhood and district scales. One question relates to the economically optimum scale at which energy autonomy should be strived for, if at all. A second question relates to the economically optimum technology combination and dispatch at different spatial scales, given the resource constraints and costs in a given local energy system. A third question relates to the implications for the local distribution network of various levels of energy autonomy and scales. The present contribution addresses these questions by developing and applying a mixed integer linear program (MILP) for decentralized generation technologies in a residential building context. The model is applied to several demand cases, from the individual building up to the neighborhood and district scales. The paper is structured as follows. The following section provides an overview of the relevant literature on this subject, from which the specific objectives of the current study and the research gaps it aims to fill are derived. Section 3 describes the methodology, Section 4 presents the results, and Section 5 includes a discussion of these results as well as a sensitivity study and a critique of the methodology. The paper closes with a summary and conclusions (Section 6).

2. Literature review

Much research has analyzed the different options for exploiting decentralized and efficient energy system potentials locally. Thereby the focus often lies on the economic, technical and/or environmental assessment of the available resources, technologies and measures. Thus decision support can be developed in the form of strategies, which can help to aid decision making relating to the implementation of specific or a whole selection of measures. In this context it is useful to distinguish between three approximately distinct scales, namely individual buildings, neighborhoods and districts, as discussed in the following subsections.

2.1. Individual buildings

Even if diverse decentralized energy technologies are exploited, it is unlikely that high levels of energetic autonomy can be achieved at the building scale without some kind of storage device. One technological option is to convert electricity into hydrogen

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[1] Energy autonomy is used in this paper to refer to the general practice of local energy generation and use. Self-sufficiency and related terms are employed to measure the degree of energy autonomy with respect to electricity (see Section 3 for details).

[2] It should be noted here that Germany has one of the highest levels of electricity system security of supply, as measured by the SAIDI, System Average Interruption Duration Index, indicator, in Europe. On average over the past years the SAIDI was at around 16 min per year for end-consumers [4].

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