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How low exergy buildings and distributed electricity storage can contribute to flexibility within the demand side

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HIGHLIGHTS

- Novel power-aware electricity tariff.
- Optimal ratio between rooftop PV and batteries in residential buildings.
- Individual selection of battery components: capacity, input and output power.

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ABSTRACT

Residential buildings are responsible for a substantial and steadily growing share of the global electricity consumption, approximately 30%. The ability to control the timing and magnitude of the aggregate electricity consumption of buildings is acquiring critical relevance. Buildings play a pivotal role in defining the shape and composition of the final electricity demand, and have an impact on the existing and projected electrical system infrastructure. This paper proposes distributed electrical storage using electrical batteries at the residential level, as an economical and technically feasible way to introduce a degree of responsiveness with the demand of residential buildings without compromising the comfort of users.

The objective of the paper is to devise the operative principles governing the relation between the grid operator and a community of low exergy (lowEx) buildings, under the assumption that the grid operator is interested in controlling the form of the aggregate electricity consumption in that community.

This paper presents a pricing policy aimed to stimulate a power-aware consumption, and consequently peak-shave the total electricity profile. The introduced pricing scheme separately addresses energy and power, and provides an incentive for buildings to invest in decentralized generation and storage technologies. The paper presents a methodology to determine the optimal amount of decentralized electrical storage and PV necessary to meet the objectives of the grid operator and allowing users to obtain a profit from the dynamic electricity tariff.

A model is used to determine the optimal battery and PV investment from the perspective of the user. The analyses show that the introduced electricity tariff triggers an equilibrium, in which users invest between 20% and 25% of the total incurred cost in battery and PV.

The PV and the battery input power were found to be mainly related to the objective of reducing the energy cost. On the other hand, the battery capacity and output power were found to be associated with the peak reduction objective. Users invest less than 10% of the total battery investment share in the battery input power. This fact indicates that contrary to a battery usage driven by the price volatility, which is proposed in many models, the battery is mainly used as power-to-energy buffer. Energy is slowly stored in the battery and rapidly released at critical peak hours.

1. Introduction

Buildings are not isolated entities, they are constituents of larger and more complex systems. The relation between a building and its environment can be characterized in terms of the different interactions and synergies that take place at the boundaries of the building. Buildings make up neighborhoods, urban landscapes, and are connected to a wide range of district utilities. There is a constant interaction in the form of energy, mass, and information between the building and its surroundings.

One such interaction is at the interface between the building and the electrical grid. Due to the nature of electricity, generation

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Nomenclature

Model's scalars

b_e	batt. capacity [kWh]
b_p^{in}	batt. input power [kW]
b_p^{out}	batt. output power [kW]
b_{η_c}	charging efficiency [%]
b_{η_d}	discharging efficiency [%]
b_η	roundtrip efficiency [%]
b_{soc}^{min}	min. SOC [%]
ϕ_p	PV maximum power [kW]
ϕ_a	PV effective area and efficiency [m^2]
γ	batt. maximum number of cycles [cycles]
τ_b	batt. calendar life [year]
τ_ϕ	PV calendear life [year]
d_{τ_d}	length of the analysis period [day]

Model's costs and parameters

r	discount rate [%]
m	maintenance rate [%]
τ_d	analysis period [year]
α	ratio grid to peak costs
ξ	power to energy conversion factor [kW/kWh]
c_e^k	cost batt. capacity unit [EUR/kWh]
c_p^k	cost batt. power unit [EUR/kW]
$c_{b_e}^f$	daily per-unit batt. energy fixed cost [EUR/(kWh·day)]
$c_{b_p}^f$	daily per-unit batt. power fixed cost [EUR/(kW·day)]
$c_{b_e}^m$	marginal cost of batt. storage [EUR/kWh]
c_ϕ^k	cost per PV power unit [EUR/kW]
c_ϕ^f	daily per-unit PV power fixed cost [EUR/(kW·day)]
NPV	net present value [EUR]
$A_{\tau,r}$	annuity

Model's vectors

$\mathbf{b}_{soc}$	batt. SOC [kWh]
$\mathbf{x}_l$	electrical load [kWh]
$\mathbf{x}_b^{in}$	elec. flowing into the battery [kWh]
$\mathbf{x}_b^{out}$	elec. flowing out of the battery [kWh]
$\tilde{\mathbf{x}}_l$	stochastic load [kWh]
$\mathbf{x}_l^d$	load for day d [kWh]
$\mathbf{x}_g$	elec. withdrawn from the grid [kWh]
$\mathbf{c}_g$	elec. prices (energy component)[EUR/kWh]
$\mathbf{x}_g^d$	elec. withdrawn from the grid on day d [kWh]
$\mathbf{c}_g^{max}$	peak prices (power component) [EUR/kW]
$\mathbf{c}_g^d$	elec. prices (energy component) for day d [EUR/kWh]
$\mathbf{c}_g'$	elec. prices (energy and power components) [EUR/kWh]
$\mathbf{k}_g^d$	maximum daily peaks [kW]
$\mathbf{c}_g^{spot}$	spot market prices [EUR/kWh]
$\mathbf{x}_l^{total}$	total electrical load [kWh]
$\mathbf{x}_g^{total}$	total electricity withdrawn from the grid [kWh]
c_g^{avg}	average electricity tariff [EUR/kWh]
$\mathbf{x}_g^{d,total}$	total electricity withdrawn from the grid on day d [kwh]

Building parameters

A_s	constructed area [m^2]
A_w	window area [m^2]
H	shape factor
U	U-value [$kW_{th}/(m^2 \cdot K)$]
C	thermal capacity [kWh/K]
$\mathbf{T}_{amb}$	ambient temperature[°C]
$\mathbf{T}_{int}$	indoor temperature [°C]
$\mathbf{Q}_{sto}$	heat stored in the building mass [kWh_{th}]
$\mathbf{Q}_{trans}^{add}$	additional losses due to heat storage [kWh_{th}]
$\mathbf{E}_e$	normalized, corrected solar irradiance [kWh/m^2]

Load generator's Markov probabilities

A	absent state
P	present state
p_t	probability that an occupant is present
μ	mobility parameter
t_{00}	prob. of staying away
t_{01}	prob. of arriving home
t_{10}	prob. of leaving home
t_{11}	prob. of staying at home

model's investments [EUR]

C	total cost
$C_{b,e}^f$	cost of battery storage
C_g	fee due to grid electricity (energy component)
C_g^{max}	fee due to daily peaks (power component)
$C_{b,e}^m$	cost of transit energy
$C_{b,p}^{in}$	cost of battery input power
$C_{b,p}^{out}$	cost of battery output power
C_ϕ	cost of PV power

and consumption have to be balanced on a per second basis. Historically, all operations necessary to keep the grid in balance were carried out from the generation side. However, a series of developments that have taken place during the last years; namely, the phasing out of nuclear power plants in Europe, policies enforcing the decarbonisation of heating and cooling systems, and the growing adoption of decentralized rooftop PV, have highlighted the pivotal role of flexible loads on balancing the grid [1,2].

The decarbonisation of the energy supply in buildings is achieved by electrifying formerly exergetic inefficient heating and cooling systems, and ensuring that the electricity is generated from safe and renewable sources. This trend towards electrification, together with the adoption of decentralized rooftop PV, results in additional challenges for the electricity utility, which we assume to be also the distribution grid operator. The objective of this paper is to explore a scenario in which the grid operator can incentivize buildings to invest in electrical batteries and PV. Decentralized electricity storage provides a mechanism to control not only the consumption linked to thermal comfort, but the total electricity profile. The resulting flexibility can constitute an alternative to upgrading the distribution grid.

The different operations, techniques, and approaches aimed at making buildings flexible and controllable are collectively referred to as Demand Response (DR) [3–5]. DR provides the possibility of shifting electricity consumption between peak and off-peak periods and, more accurately, of matching the load of the building with the available generation on a real-time basis. There are multiple ways in which these objectives can be met: load curtailment [6,7,4,3], dynamic and time of use tariffs [8,6,9–11], incentive-based programs [6], load management [6,7,3], storage [10,11], among others. This paper focuses on the orchestrated deployment of electrical batteries and PV modules, and on the definition of the accompanying pricing policy.

In contrast to direct load DR strategies [3], or approaches stimulating user's change in consumption habits [12], the approach adopted in this work strives to be independent from the user comfort. The responsiveness in the demand is introduced by means of battery, as in [13–18]. In contrast to the models presented in [15–