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Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances

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HIGHLIGHTS

- Modelling and optimization of HES and CES for prosumers with smart appliances.
- Economic feasibility of both HES and CES using real data of 39 households in a pilot project.
- Sensitivity analysis considering different sizes and prices of storage systems.
- PV self-consumption has a large impact on annual saving achieved by storage and influences the PBP.
- Under current investment costs of storage, both HES and CES are economically infeasible.

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ABSTRACT

The emergence of Decentralized Energy Resources (DERs) and rising electricity demand are known to cause grid instability. Additionally, recent policy developments indicate a decreased tariff in the future for electricity sold to the grid by households with DERs. Energy Storage Systems (ESS) combined with Demand Side Management (DSM) can improve the self-consumption of Photovoltaic (PV) generated electricity and decrease grid imbalance between supply and demand. Household Energy Storage (HES) and Community Energy Storage (CES) are two promising storage scenarios for residential electricity prosumers. This paper aims to assess and compare the technical and economic feasibility of both HES and CES. To do that, mathematical optimization is used in both scenarios, where a Home Energy Management System (HEMS) schedules the allocation of energy from the PV system, battery and the grid in order to satisfy the power demand of households using a dynamic pricing scheme. The problem is formulated as a Mixed Integer Linear Programming (MILP) with the objective of minimizing the costs of power received from the grid. Data from real demand and PV generation profiles of 39 households in a pilot project initiated by the Distribution System Operator (DSO) 'Enexis' in Breda, the Netherlands, is used for the numerical analysis. Results show that the self consumption of PV power is the largest contributor to the savings obtained when using ESS. The implementation of different ESS reduces annual costs by 22–30% and increases the self-consumption of PV power by 23–29%. Finally, a sensitivity analysis is performed which shows how investment costs of ESS per kWh are crucial in determining the economic feasibility of both systems.

1. Introduction

Over the last couple of decades, global power demand has increased significantly across all sectors [1]. In the residential sector, electrification is an important contributor to the increasing power demand [2]. At the same time, both European and Dutch national policy dictate that efforts should be made to reduce carbon emissions and increase the share of renewable energy in order to counter climate change [3,4]. This has led to the rapid development and application of renewable energy technologies. In the residential sector, this trend has manifested itself by a sharp increase of Photovoltaic (PV) systems on residential rooftops.

The intermittent nature of Decentralized Energy Resources (DERs), combined with the rising electricity demand causes difficulties for the grid operator in maintaining the grid's reliability and stability. The peak demand of electricity usually occurs at a different interval from the supply peak provided by DERs, creating a mismatch between renewable generation profiles and demand profiles [5]. Demand Side Management (DSM) is one of the concepts used to optimize the matching between power supply and demand. DSM is defined as 'actions that influence the way consumers use electricity in order to achieve savings and higher efficiency in energy use' [6]. DSM can be used to optimize self-consumption levels of DERs, thereby decreasing the need for energy

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Nomenclature

Abbreviations

CES	community energy storage
DER	decentralized energy resource
DSM	demand side management
DSO	distribution system operator
EMS	energy management system
ESS	energy storage systems
HEMS	home energy management system
HES	household energy storage
LCOE	levelized cost of energy
MILP	mixed integer linear programming
PBP	pay back period
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
RES	renewable energy sources
RTP	real time pricing
S1PW1	scenario1: HES with Powerwall 1
S1PW2	scenario1: HES with Powerwall 2
S2CES	scenario2: CES with current operating size
S2CESopt	scenario2: CES with optimal size
SoC	state of charge
WM	washing machine

Indices

a	index for shiftable appliances, $a \in \{1,2,...,A\}$
i	index for households, $i \in \{1,2,...,N\}$
t	index for time-slots, $t \in \{1,2,...,T\}$

Sets

A^i	number of shiftable appliances in household i
N	number of households
T	number of time-slots for the considered time horizon

Parameters

η_{ch}	battery charging efficiency [–]
η_{dis}	battery discharging efficiency [–]
$C^i_{bat,CES}$	battery share size of the CES allocated to i [kWh]
$C^i_{bat,HES}$	battery capacity of the HES in i [kWh]
c^t	cost of power absorbed from the grid at t [Euro/kWh]
Cap^i_{CES}	optimal battery share size for i [kWh]
$Cap_{CES,opt}$	optimal size of CES [kWh]
$CP^{a,t,i}$	consumer preference for the activation of a in i at t (i.e., on or off)
E^a_{sl}	daily energy consumption requirement of a [kWh]
$E^i_{grid,inj}$	maximum daily injected energy to the grid the battery should be able to store in i [kWh]
$P^{t,i}_{peak}$	maximum allowed power for i in each t [kW]
P^a_{max}	upper limit of power assignment to a [kW]
P^a_{min}	lower limit of power assignment to a [kW]
$P^i_{bat,max}$	maximum power that can charge/discharge the battery in i [kW]
$P^i_{grid,max}$	maximum allowed power from/to grid in i [kW]
$P^{t,i}_{nsl}$	non-shiftable load in household i at t [kW]
r^a	number of time-slots a should run before it can be switched off
Sh^i	household i share of the CES [%]
SoC_{max}	maximum battery SoC [%]
SoC_{min}	minimum battery SoC [%]
SoC_0	initial battery SoC [%]

Variables

$p^{a,t,i}$	power demand of a in i at t [kWh]
$p^{t,i}$	power action in i at t [kW]
$p^{t,i}_{bat,ch}$	battery charging power in i at t [kW]
$p^{t,i}_{bat,dis}$	battery discharging power in i at t [kW]
$p^{t,i}_{grid,abs}$	power absorption from the grid in i at t [kW]
$p^{t,i}_{grid,inj}$	power injection to the grid from i at t [kW]
$P^{t,i}_{pv}$	power harvested by the local PV system of i at t [kW]
$p^{t,i}_{sl}$	shiftable load in i at t [kW]
$SoC^{t,i}$	battery state of charge in i at t [%]
$y^{a,t,i}$	a binary decision variable indicates whether a at t in i is on (1) or off (0)
$z^{a,i}$	a binary decision variables indicates when a starts operating in i

Economic indicators

γ	discount rate [%]
c^i_{annual}	annual costs of electricity in i [Euro]
I_{CES}	investment cost in CES [Euro]
I_{HES}	investment cost in HES [Euro]
L	lifetime of storage system [years]
$LCOE^i$	levelized costs of electricity for i [Euro/kWh]
PBP^i_{CES}	number of years before the investment in CES is recovered for i [years]
PBP^i_{HES}	number of years before the investment in HES is recovered for i [years]
S^i	costs savings per year of power absorbed from the grid after and before using the storage [%]

transportation across the grid. DSM is most promising for controllable and shiftable load, such as Plugin Hybrid Electric Vehicle (PHEV) and flexible appliances, which can be run at flexible time schedules in the scope of a day [5]. However, not all household load is suitable for DSM. Some appliances are either bound to a specific time of use (e.g., cooking) or provide low capabilities for shifting power consumption for relatively long time periods (e.g., cold appliances). Other appliances do not use significant amounts of energy to be suitable for DSM (e.g., electronics). Therefore, it is almost impossible to match all households electricity demand with the available supply at a certain time.

Energy Storage Systems (ESS) can be used as a complementary solution to improve the self-consumption of electricity generated by DERs [7,8]. Surplus energy can be stored temporarily in a Household Energy Storage (HES) to be used later as a supply source for residential demand [9]. The battery can also be used to react on price signals [10]. When the price of electricity is low, the battery can be charged. When the price is high, the battery can be discharged and make profit by selling electricity back to the grid. However, ESS costs have been identified as a possible downside of residential battery exploitation [11,12]. Currently it might not be possible to earn back the investment costs of the battery since selling back energy to the grid can be more profitable. In the Netherlands, the feed-in tariff for electricity generated by DERs is identical to the electricity price, therefore there is no incentive for household to deploy a HES system [13].

Recent policy developments indicate a decreased tariff in the future for electricity sold back to the grid by households with DERs [4]. Therefore, self-consumption is becoming more attractive for households in order to improve the 'financial utilization' of their PV system. By