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Solar plus: Optimization of distributed solar PV through battery storage and dispatchable load in residential buildings

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HIGHLIGHTS

- Analysis of residential PV optimization with battery storage and load control.
- Economic analysis of PV optimization in a variety of rate environments.
- Findings show that load control in particular improves the economics of PV.
- Storage and load control improve PV value in challenging rate contexts.

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ABSTRACT

As utility electricity rates evolve, pairing solar photovoltaic (PV) systems with battery storage has potential to ensure the value proposition of residential solar by mitigating economic uncertainty. In addition to batteries, load control technologies can reshape customer load profiles to optimize PV system use. The combination of PV, energy storage, and load control provides an integrated approach to PV deployment, which we call "solar plus". The U.S. National Renewable Energy Laboratory's Renewable Energy Optimization (REopt) model is utilized to evaluate cost-optimal technology selection, sizing, and dispatch in residential buildings under a variety of rate structures and locations. The REopt model is extended to include a controllable or "smart" domestic hot water heater model and smart air conditioner model. We find that the solar plus approach improves end user economics across a variety of rate structures – especially those that are challenging for PV – including lower grid export rates, non-coincident time-of-use structures, and demand charges.

1. Introduction

The temporal mismatch between solar photovoltaic (PV) system output and residential electricity demand is one of the primary challenges to wide-scale residential PV deployment [1–4]. PV output often exceeds residential electric loads during the day but falls short of demand in the late afternoon and evening when residential load tends to increase. Grid export – where excess PV output is sold to the electric grid – has provided an economic solution to this temporal mismatch. Through grid export policies such as net metering (U.S.) and feed-in tariffs (Europe, Australia, Asia), customers earn returns from full PV system output regardless of whether that output is used on site [5,6]. However, grid export rates are declining in many major PV markets around the world [7,8]. Lower grid export rates incentivize customers to reduce excess output and maximize on-site PV self-use. Other proposed and implemented residential rate reforms such as time-of-use (TOU) rates and customer demand charges pose further challenges to future residential PV deployment [7].

Solar plus storage has emerged as an alternative to grid export in evolving rate environments [7,9–12]. Energy storage solves the temporal mismatch by storing excess PV output in a battery for later consumption. A growing body of literature and new PV product bundles indicate that in addition to batteries, load control technologies can reshape customer load profiles to optimize PV system use [13–19]. We use a time series optimization model formulated as a mixed integer linear program to explore the economics of solar plus storage and load control under different rate structures. The combination of PV, energy storage, and load control provides an integrated approach to PV deployment, which we call "solar plus".[1]

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[1] This paper builds on an analysis previously presented in a National Renewable Energy Laboratory working paper: "Solar Plus: A Holistic Approach to Distributed Solar PV."

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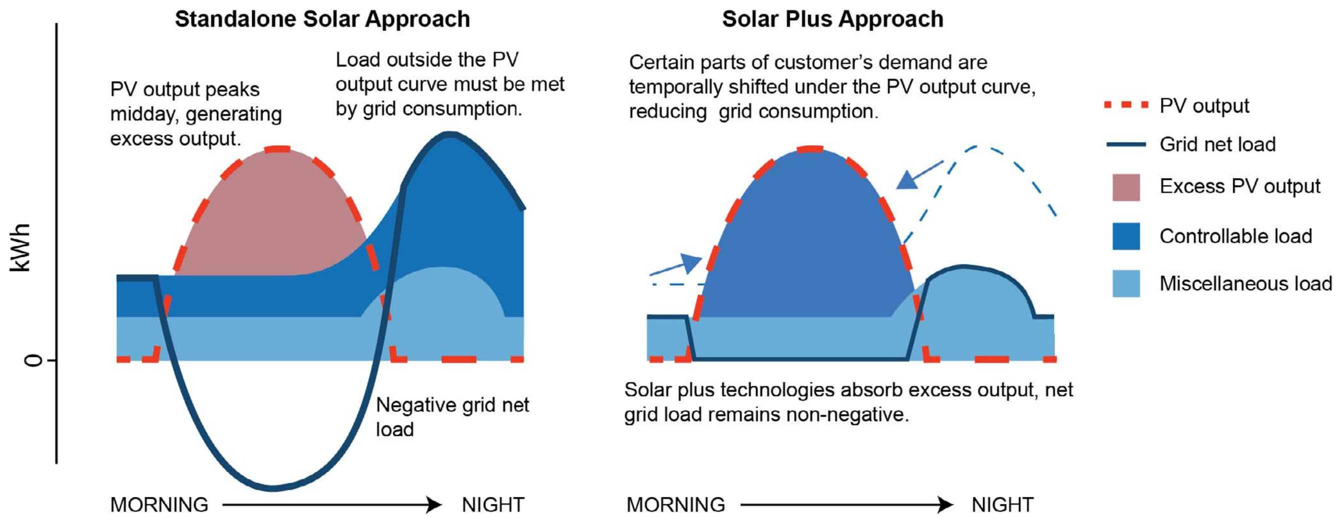

Fig. 1. Customer load shifting through solar plus. Grid net load is the total customer load at the utility meter; negative grid net load reflects excess PV output exported to the grid.

2. Solar plus

In solar plus systems, load control technologies shift electric load to coincide with PV output (Fig. 1) [16–18]. For instance, PV customers can manually shift load by using deferrable devices, like laundry machines, during the midday solar peak rather than in the evening. Solar plus automates this process by calibrating home devices to maximize their use of PV rather than grid electricity. Any remaining excess PV output may be delivered to a battery and then to the grid as a last resort. Solar plus can improve overall end-user economics by increasing PV self-use, reducing grid exports, performing grid arbitrage (where customers pay TOU rates), reducing demand charge payments (where applicable), and reducing customer electricity payments.

A variety of home appliances can be included in a solar plus system such as domestic water heaters, air conditioning (AC) units, heat pumps, and washing machines. This study focuses on programmable or "smart" domestic water heaters and AC units (Fig. 2), given that load control through thermal storage has been shown to have greater impacts than other controllable home appliances [17,19]. Conventional electric domestic water heaters maintain a set tank temperature by heating water instantaneously following hot water draws (Fig. 3, top). Programmable domestic water heaters can preheat water with PV output then allow the tank temperature to drift down to a minimum temperature without reheating with grid electricity (Fig. 3, bottom). Conventional AC units maintain internal home temperatures around some target temperature (Fig. 4, top). Programmable units can precool the home with PV output and allow temperatures to drift up toward a maximum temperature without re-cooling with grid electricity (Fig. 4, bottom).

Electric vehicles (EVs) can potentially enhance the value of solar plus systems [20]. A typical EV has around 30 kWh of electrical storage capacity [21], far greater than the capacity of current residential battery offerings and the thermal capacity of smart domestic water heaters and AC units. EV owners could use this storage capacity to increase PV self-use by charging vehicles during peak PV output hours. In this sense, PV optimization is an ancillary benefit of EV ownership. EV ownership remains relatively uncommon. It is unclear whether PV owners would be willing to invest in EVs for the purposes of PV optimization. Further, to the extent that PV optimization is part of the value proposition of EV ownership, it is unclear how to apportion EV cost premiums between the added benefits of EV ownership (e.g., lower fuel costs) and the solar plus capabilities. To avoid speculating about the willingness of PV owners to invest in EVs, we exclude EVs from our analysis. EV integration into solar plus systems is a proposed area of future research.

A growing body of research explores solar plus in a variety of configurations and contexts. The majority of this literature analyzes the technical capacity of solar plus to increase PV self-use, with limited economic analysis based on simplifying assumptions about the value of PV self-use [13–17,22,23]. In a review of this research, Luthander et al. [18] find that batteries (including EV batteries) generally increase PV

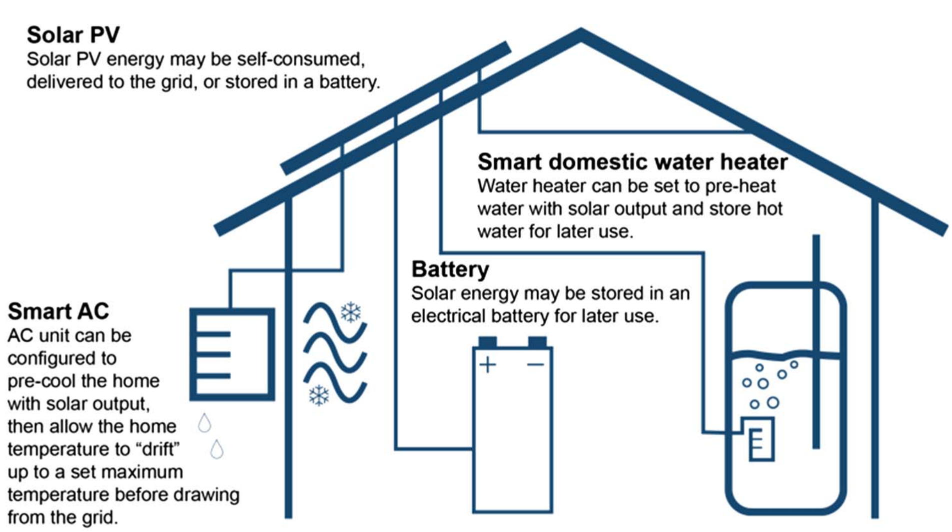

Fig. 2. The solar plus home.