Representing the Solar Rebound Effect in an Energy System Model – Effects on Transformation Pathways

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Overview

A successful transformation to sustainable energy systems relies on the extensive expansion of renewable energy sources and efficient usage of energy. A critical aspect is the solar rebound effect (SRE), where energy savings from domestic photovoltaic (PV) adoption may be partially or entirely offset by increased electricity consumption of private households [1]. The effect has not yet been considered in model-based energy system analyses, even though solar PV will play a major role in future energy systems [2]. Against this background, the research question is: How does SRE integration in energy models influence long-term planning and the expansion of renewable energy technologies?

Methods

The main challenge of implementing the SRE into energy models lies in its empirical foundation. Most existing studies report an average SRE at an aggregate and annual level ranging from 7.7% to 33% of additional electricity consumption in relation to solar PV generation [1, 3]. This leaves open the times when households increase their electricity consumption, which is of central importance for energy models with mostly hourly resolution. Two studies indicate that the SRE is higher during summer and may also occur during off-peak times when the sun is not shining [3, 4]. Due to a lack of comprehensive smart meter data, we have opted for a scenario-based analysis considering existing empirical studies. The scenarios include two extremes: (I.) ***simultaneous***, where the SRE fully aligns with solar PV generation (leading to a higher SRE during daytime and the summer), and (II.) ***sweeping***, where the effect is independent of direct solar power generation and evenly distributed over time. A further scenario (III.) ***mixed***[1], captures the tendency of the SRE to peak during daytime hours while also occurring during off-peak periods, as highlighted in previous studies [4].

The scenarios are integrated into an optimization model (E2M2s [5, 6]) that considers the development of the European energy system until 2050. It is formulated as a linear problem with recursive optimization across yearly stages. This approach ensures that the SRE emerges in the following stage, meaning it does not directly impact the initial investment decisions in solar PV. The objective function minimizes total system costs (including variable production and investment costs) and is subject to side constraints, such as generation, storage, and capacity restrictions. Considering the differentiation between private households and other sectors, the SRE enters the balance equation for electricity demand. It is important to note that the SRE does not result in a proportional increase in demand across the entire system; instead, it leads to a rise in electricity consumption, specifically within households that generate solar power. This additional demand is directly proportional to these private households' higher solar power generation.

Results

Model calculations reveal that the SRE offsets the expected efficiency gains from private households. This increases the expansion needs of renewable energy sources and costs to reach climate neutrality. Considering an extreme scenario with an SRE of 33% based on [1], the additional demand volumes can reach up to 306 TWh[2] in Europe in 2050 (Table 1). The additional demand increases total system costs between €72.23 bn. (Simultaneous) and €82.82 bn. (Sweeping) (Table 2). In the simultaneous scenario, power generation relies more on solar PV, while onshore wind, pumped storage, and hydrogen production are used less (Figure 1). This is because the SRE aligns with PV production, concentrating demand and PV generation at midday. The sweeping scenario spreads the SRE evenly throughout the day, creating a more balanced load. This scenario increases the use of battery storage and hydrogen technologies, driven by a greater need for intraday and inter-seasonal flexibility. The mixed scenario results in a moderate increase in PV generation and greater use of storage technologies, including batteries for higher short-term flexibility needs and hydrogen for long-term storage.

[1] A portion of the SRE is directly proportional to solar PV generation, while another portion shifts to evening hours (50% sweeping/50% simultaneous).
[2] This figure nearly equals Italy's electricity demand in 2023 [7], one of the world's top 10 largest economies.

	Simultaneous SRE	Mixed SRE	Sweeping SRE
Galvin Scenario: 33%	7,564.36 TWh (+ 4.22%)	7,590.23 TWh (+ 4.57%)	7,638.80 TWh (+ 5.24%)

Table 1: *Demand volumes including SRE (rounded values) for the year 2050 (compared to a reference scenario with 0% SRE)*

	Simultaneous SRE	Mixed SRE	Sweeping SRE
Galvin Scenario: 33%	+ €72.23 bn. (+ 2.95%)	+ €72.44 bn. (+ 2.96%)	+ €82.82 bn. (+ 3.39%)

Table 2: *Total system cost differences (rounded values) accumulated for the period 2030–2050 (compared to a reference scenario with 0% SRE)*

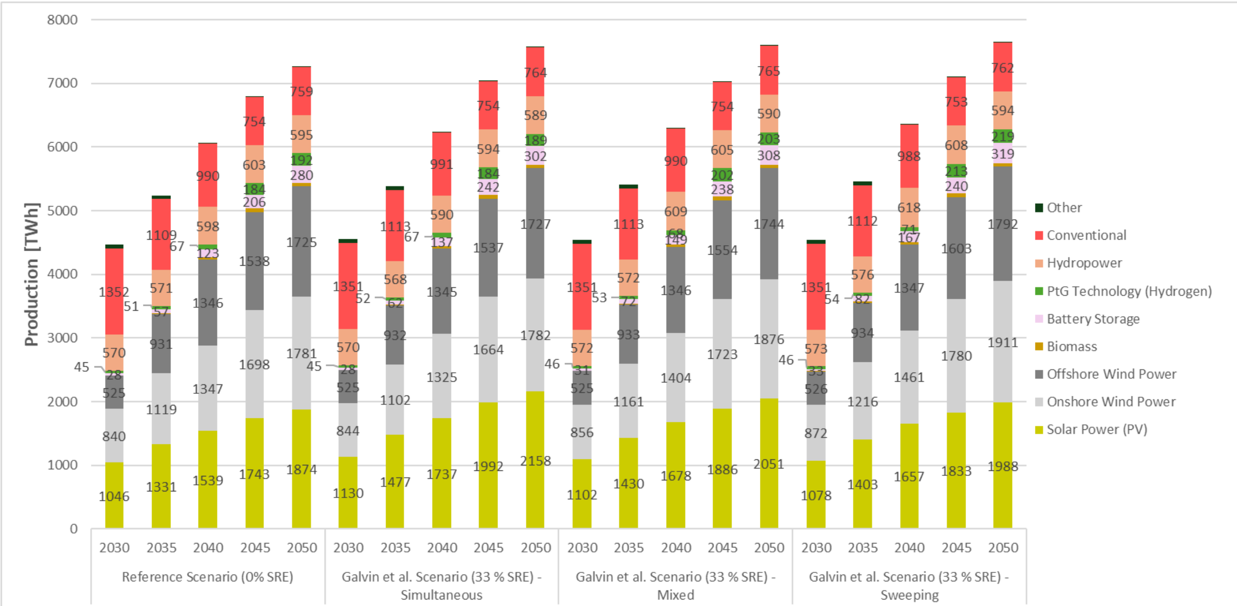

Figure 1: *Electricity generation mix (in Europe) under the reference scenario compared to the different approaches in the extreme scenario*

Conclusions

Representing the SRE in an energy system model reveals considerable effects of the rebound effect on capacity expansion and flexibility requirements driving overall system costs. Depending on the temporal alignment of solar PV generation and the additional electricity consumption due to the SRE, system costs increase by up to 3.4 %, which underpins the economic relevance of the effect. Moreover, using an energy system model allows us to study infrastructure needs and system operation interactions. Future work will improve the empirical foundation and deepen the analysis of interactions at the level of the European energy system.

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