Exploring the future of the behind-the-meter energy transition: a modelling approach

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Overview

A two-fold energy transition is underway, one occurring at grid-scale and another occurring at the scale of individual households and organisations. The latter "behind-the-meter" energy transition is driven by astonishing falls in the cost of photovoltaics (PV) and battery energy storage solutions (BESS), attractive feed-in tariffs and by persistently high grid electricity prices.

Traditional techno-economic techniques used for power system planning at grid scale do not describe how households make energy choices. A different set of methods, drawn from the social sciences, is needed. Modelling of PV-BESS uptake by consumers requires an understanding of the heterogenous financial rewards, cognitive biases and social influences on decision making.

BESS offers two streams of financial reward to households (1) solar power management and (2) tariff arbitrage. In power systems dominated by variable renewable energy, time-of-use pricing incentivises BESS adoption both at the grid scale and behind-the-meter. Modelling presented here predicts that even in Ireland—a country with some of the lowest solar potentials globally—PV-BESS penetration can reach significant levels, even under relatively pessimistic cost scenarios. This underscores the growing role of cost reductions in shaping the behind-the-meter energy transition, exceeding the effect of policy interventions.

Despite the distinct analytical frameworks required to model grid-scale and behind-the-meter transitions, their interaction is becoming increasingly important. This interplay will require greater attention from system planners and policymakers. One extreme example of such interactions is grid abandonment. While grid prices in Europe are high, seasonality of solar power suggests that consumers will retain grid connections, provided fixed costs remain sufficiently low. However, recent studies indicate that grid abandonment is already economically viable in parts of the U.S., where grid costs are substantially lower than in Europe (Sadat & Pearce, 2024).

This paper models the likely range of outcomes for Ireland, showing how installed PV and BESS capacities depend on the key cost and policy assumptions.

Methods

Forecasting technology adoption is challenging due to the extreme heterogeneity of consumers, even with perfect price forecasts. This paper addresses this complexity using a social science simulation approach. An agent-based model (ABM) is micro-calibrated using survey data collected from 1,225 Irish households in late 2024, where respondents indicated their preferences for solar PV adoption. This survey builds on earlier work (Mukherjee & Ryan, 2020), and captures a broad range of physical, demographic, and attitudinal attributes. The ABM is trained on the survey dataset using machine learning techniques. A subsequent macro-calibration stage ensures that the model aligns with observed solar uptake rates by accounting for hypothetical bias in the survey responses.

A detailed financial return on investment (ROI) model was developed, defined as the percentage reduction in net present value (NPV) after factoring in loan costs, where applicable. For an agent to invest, their expected ROI at a given time step must exceed an individually determined threshold or risk premium. The ABM also incorporates a social influence effect, capturing the impact of peer behaviour on adoption decisions. Physical constraints, such as limited rooftop space, are included. Agents with restricted solar capacity may still adopt BESS if it is advantageous.

The key financial parameters influencing adoption include:

- Technology costs (including grants).

- Grid electricity price and feed-in tariffs.
- Time-of-use price differentials.
- Seasonality of the solar resource.

Scenarios are developed based on combinations of these parameters, enabling predictions of PV and BESS adoption patterns. The ABM is executed repeatedly (typically 96 runs per scenario) to estimate the expected installed capacities under diverse conditions.

Results

A sample of uptake projections for 2030 is shown in Table 1. Here, the base scenario has a 2030 PV cost of €200/kW and a BESS cost of €200/kWh. This gives nearly 2GW of solar PV capacity and nearly 1 GWh of BESS capacity by 2030 in Ireland. Self-consumption (SC) declines strongly if feed-in tariff increases (scenario D). While high feed-in tariffs incentivise solar PV capacity and disincentivise storage, high time-of-use tariff differentials incentivise storage. High rates of self-consumption and household BESS capacity lowers pressure on the power network.

Table 1 Residential PV-BESS uptake rates modelled in a sample of scenarios for Ireland.

Scenario	Uptake %	SAR %	S GW	S_1 GW	S_2 GW	Storage GWh	solar TWh	exports TWh	SC[a] %	CF[b] hours
A	15.4	64.8	1.92	1.11	0.80	0.96	1.1	0.6	43.2	1.65
Base	14.9	60.9	1.85	1.07	0.78	0.80	1.0	0.6	42.4	1.65
C	14.2	46.8	1.55	0.98	0.57	0.54	0.9	0.5	42.0	1.69
D	17.6	17.1	2.78	1.45	1.33	0.43	1.5	1.1	24.3	1.58

[a] Self consumption or $1 - \text{exports}/\text{solar}$

[b] Capacity factor in effective hours per day.

The scenarios shown in Table 1 have relatively high technology cost and assume no time-of-use pricing, yet they already suggest significant impact on the power grid. Outcomes as a function of the key financial parameters can be summarised in a "phase diagram" showing the different types of behind-the-meter energy systems that may arise. Note that, in the limit of very low cost scenarios that appear increasingly likely to be realised, we find that uptake rates become limited by household inertia and other constraints.

Conclusions

The two ongoing energy transitions, at grid-scale and behind-the-meter, are likely to interact and shape the future power system in complex and potentially unforeseen ways. Social science modelling techniques can assist policymakers in understanding and managing these interactions to ensure a coherent future for the power system. Taking account of system adequacy and network pressures, policymakers can target desired outcomes in terms of specific PV and BESS capacities through appropriate use of feed-in tariff and time-of-use/dynamic pricing incentives.

References

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