Regional residential battery storage diffusion pathways in Hungary

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In this paper, we present a novel simulation model designed to estimate the regional diffusion of residential battery storage and its associated effects on the electricity system under alternative policy scenarios. A significant shortcoming of existing models for residential battery storage is their failure to consider regional variations, which results in diffusion estimates that are inherently inaccurate. Such regional disparities may stem from factors such as climatic conditions, income levels, and levels of innovation. A similar pattern is evident with solar panels, where the adoption rates exhibit considerable regional variation. Such discrepancies in the adoption of solar panels and residential battery storage can result in local grid imbalances.

The model simulates the number of residential battery adopters by taking into account both financial and non-financial factors. Agents with typical load profiles make annual decisions on whether to invest in battery storage. This study examines the diffusion of residential battery storage in Hungary under various policy scenarios, including subsidy schemes with different levels of ambition. Our findings suggest that an ambitious subsidy package of EUR 838 million could result in a total residential battery storage capacity of approximately 4 GWh, which would lead to a reduction in evening peak load of between 2.5 and 5%.

Keywords:
battery storage,
technology diffusion,
regional modelling,
electricity system,
load shifting

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Introduction

'To unleash further rapid growth of solar and storage and its benefits, we need a comprehensive strategy for electricity storage, and this includes an EU target of at least 200 GW by 2030' (SolarPower Europe 2022). As the proportion of intermittent renewable energy sources in the electricity system increases, the need for more flexibility is growing. In 2022, an 83% surge in the installation of residential battery storage occurred across Europe. Most batteries were purchased alongside photovoltaic (PV) systems, indicating that approximately one in every four new PV systems now includes battery storage (Murray 2023).

Although increased attention has been paid to the systemic impacts of residential battery storage, limited research comprehensively addresses combined household and system perspectives (Fett et al. 2021). A model-based study by Jägemann et al. (2013) analysed the influence of Germany's regulatory framework on residential battery storage investment and its impact on the system. The authors employed two optimisation models; one in which households minimise their costs by investing in PV and battery systems, and the other optimises the electricity system by investing in large-scale generation technologies. However, the study overlooks significant factors, e.g. the model assumes that all households invest in battery storage once it becomes profitable to do so, ignoring the uncertainties and non-financial factors that can influence investment decisions. Such factors can be addressed using a diffusion model.

Say et al. (2019) proposed a bottom–up simulation model based on real household data from Australia. The model determines the optimal sizes of PV and battery storage systems under different tariff schemes. In a subsequent study (Say et al. 2020), the authors expanded this approach by integrating household simulation with an optimisation model for Western Australia's electricity system, enabling the analysis of the effects of increased residential battery storage. However, this model considers only a single future year (2030); therefore, it is incapable of tracking the diffusion pathway. Yu (2018) examines the impact of residential battery storage in France, estimating the costs and changes in electricity demand that would result from the installation of PV and battery systems in all households. However, this study also failed to consider the diverse profiles of households and PV systems as it assumes direct investment without a diffusion model and neglects considering the impact of operational strategies.

Several diffusion models have been proposed for residential battery storage deployment. A Europe-wide analysis was conducted using the ELTRAMOD electricity system optimisation model and a diffusion model to estimate the total installed battery storage capacities in all countries (Klingler et al. 2019). In their study, Schwarz et al. (2019) employed an agent-based model to analyse the diffusion of residential battery storage in California under different policy scenarios. However, the study did not consider non-financial factors that can influence household decision-making and simplified the representation of the Californian wholesale market, which limited its ability to capture long-term dynamics. Finally, Fett et al. (2021) proposed a novel modelling framework combining prosumer and agent-based electricity market simulations that were implemented for Germany and neighbouring nations. The prosumer simulation incorporated a calibrated diffusion model that considered non-financial factors that influence households' investment choices. Households' social and economic characteristics exert a profound influence on consumers' choices regarding environmentally conscious decisions (Vona 2023). This approach enables a detailed analysis of transformation pathways, considering both households and utilities and their interdependencies.

However, previous research has not typically considered regional aspects of residential battery storage diffusion. The patterns of solar PV distribution demonstrate that PV diffusion is spatially uneven (Thormeyer et al. 2020), and the regional climate also has a major influence on how energy is used (Dubois et al. 2023). The intermittent nature of renewable energy sources causes local issues within the grid, which is why the regional distribution of residential battery storage is of considerably important concern. Accurately predicting battery storage diffusion at the regional level can inform infrastructure development planning.

This study proposes a regional simulation model to simulate the diffusion of residential batteries and subsequent impact on the electricity system. The model incorporates financial and non-financial factors in agents' decision-making, using a regional Bass diffusion model. The model also considers a variety of household and solar profiles, calculating the net present value distribution of battery investment for each combination of profiles, encompassing electricity usage, climate, labour costs and battery cost. The outcomes are then fed into a Bass diffusion model to determine the number of battery adopters for each year of the simulation at the NUTS3 regional level. Finally, the charging and discharging patterns of the batteries are calculated to assess each profile's overall impact on the electricity system.

Although multiple approaches are available for modelling the diffusion of residential batteries such as agent-based modelling (Schwarz et al. 2019, Danielis et al. 2023, Schiera et al. 2019), we propose employing the technology diffusion simulation approach with the intention of connecting our model to the FTT: Power (Mercure 2012) power sector model in future work.

We use the model to simulate the number of residential battery adopters in the Hungarian electricity market under different policy scenarios. The Hungarian electricity system has seen a remarkable increase in solar capacity. The revised Hungarian National Energy and Climate Plan has increased the original solar capacity target from 6–6.5 GW by 2030 to 12 GW (Hungarian Ministry of Energy 2023a). However, this rapid growth has led to grid integration issues. In October 2022, the government implemented a temporary suspension on applications for new grid connections, restricting solar panel owners to self-consumption of the energy they produce. Moreover, the net metering system applied to rooftop PV owners was modified to gross metering. In light of the grid integration problems, the government unveiled a new subsidy scheme with an almost EUR 200 million budget, with the objective of promoting the installation of rooftop solar PVs with battery storage systems, where battery storage cannot exceed 10 kWh (Hungarian Ministry of Energy 2023b). All Hungarian households are eligible for the subsidy, provided that they own an apartment in a building with up to six apartments. The registration process commenced on 15 January 2024, with the installation of the solar system with battery storage required to be completed within 24 months of a successful application. In our modelling, we consider three scenarios, a baseline scenario with no support for battery installation, a moderate support scenario and an ambitious support scenario. We also evaluate the effectiveness of two distinct support frameworks in terms of the overall number of adopters and regional discrepancies.

The remainder of this paper is organised as follows. First, the regional diffusion model is outlined and a brief description of the inputs is provided. Then, different scenarios of residential battery storage diffusion and their impacts on the electricity system are discussed. Finally, the conclusions are summarised.

Materials and methods

The proposed regional diffusion model employs a two-step approach to estimate the number of battery adopters. First, we employ a net present value (NPV) calculation, similar to that described by Fett et al. (2021) to estimate the proportion of the total population that perceives the battery investment as beneficial. The decision of whether to invest in battery storage is dependent on the household's load and solar profile. The solar profiles and the shares of the different load profiles vary across regions, therefore, it is essential to incorporate regional specifics into the model. Subsequently, we feed the potential population into regional Bass diffusion models that calculate the actual number of adopters. This approach enables the model to initially assess the financial factors underlying the investment decision, including non-financial factors. In their analysis, Cardenas et al. (2017) proposed that the Bass model can be employed to ascertain the number of households that are familiar with the technology to assess the economic viability of technology adoption. We apply the Bass diffusion model as the final step of the modelling process to ensure the S-shaped trajectory of technology diffusion. At the electricity system level, we assess the changes in the total load curve and the peak shaving potential of residential batteries.

NPV calculation

The model considers multiple regions, household load profiles and consumption sizes (indexed with r, p and s, respectively). The region determines households' solar profile and the labour cost of the battery installation, the load profile determines when the battery is charged and discharged and the consumption size determines the size of the battery to be installed. The model assumes that batteries are installed alongside solar PVs and charged from excess solar energy. A battery is charged when the solar PV generates more electricity than the household consumes. The size of the solar PV is determined to match the household's annual consumption.

Although prosumers consider various important factors when making investment decisions, they do not have perfect information concerning the future benefits of residential batteries. The model simplifies the investment decision to provide a more accurate representation of prosumers in reality. The NPV calculation adheres to the current compensation scheme (gross metering) applied to small household power plants in Hungary. The NPV calculation involves the following steps.

First, we calculate the annual benefit of the battery by determining the total amount of energy stored in the battery over the course of a year *(EnergyStored)* and multiplying it by the battery's efficiency *(Eff)* and the depth of discharge of the battery *(DoD)*, which is assumed to be the useful energy used from the battery. The useful energy is then multiplied by the difference between the electricity price (*ElecPrice*) and the feed-in tariff *(FeedInTariff)*. *ElecPrice* represents the price at which the home would have to purchase electricity from the grid, and the *FeedInTariff* is the price at which a home could sell the electricity generated by their solar PV.

It is important to note that daily energy storage is limited by the size of the battery and the depth of discharge, allowing a maximum of one charge cycle per day. The depth of discharge limitation is added to avoid shortening the battery's lifetime. We construct the following equations:

$$AnnualBenefit_{r,p,s} = EnergyStored_{r,p,s} \times Eff \times DoD \times (ElecPrices - FeedInTariff) \tag{1}$$

Then, the discounted benefit of the battery over its lifetime is calculated in Eq. (2).

$$DiscBenefit_{r,p,s} = \frac{AnnualBenefit_{r,p,s}}{i-g} \times \left(1 - \frac{1+g}{(1+i)^{Lifetime}}\right) \tag{2}$$

where i is the real discount rate assumed by the prosumers, g is the annual electricity price growth and *Lifetime* is the battery's lifetime in years.

After the discounted benefit of battery installation is calculated, investment costs are assessed as follows:

$$InvCost_{r,s} = (BatteryCost + LabCost \times IncomeAdj_r) \times BatterySizes \times (1 - Subsidy) - LumpSum \tag{3}$$

where *BatteryCost* is the price of a battery with 1 kWh storage capacity, $BatterySize_s$ is the assumed battery size in kWh for the corresponding consumption size, *LabCost* is the installation labour cost and $IncomeAdj_r$ is an adjustment to the labour cost based on the region's average income level. *Subsidy* represents an ad valorem support for battery installation, and *LumpSum* is also a subsidy in the form of a lump sum payment.

We then calculate the NPV of battery installation as the difference between the discounted benefit and the investment costs as follows:

$$NPV_{r,p,s} = DiscBenefit_{r,p,s} - InvCost_{r,s} \tag{4}$$

Finally, we generate a normal distribution with a mean equal to $DiscBenefit_{r,p,s}$ and a standard deviation of *CostStd*, where *CostStd* is the relative standard deviation of battery cost. The potential population of the Bass model is determined using the probability calculated from the discounted benefit distribution. The share of the total population of a region defined as the potential population in the Bass model in region *r* in year *t* is determined as follows:

$$\begin{aligned} PopShare_{r,p,s} &= 1 - P\left(DiscBenefit_{r,p,s} \leq InvCost_{r,s}\right) = \\ &= 1 - \int_{\infty}^{InvCost_{r,s}} \frac{1}{\sqrt{2\pi}CostStd^2} e^{-\frac{\left(DiscBenefit_{r,p,s} - InvCost_{r,s}\right)^2}{2CostStd^2}}. \end{aligned} \tag{5}$$

However, it is assumed that a small proportion of the population are ’innovators’ who invest in new technologies regardless of NPV.

In summary, the NPV calculation determines the proportion of regional households for which the installation of the battery is beneficial. We then use this as the potential population for the Bass diffusion model.

Bass diffusion model

Although the NPV calculation represents a diverse range of prosumers distinguished by investment cost, consumption size, load profile and solar profile, financial return is not the only influencing factor of investment decisions. Even if the NPV calculation indicates that investing in batteries is beneficial, non-financial factors such as insufficient information and uncertainty about the costs of battery storage can impede rapid penetration (Steinbach 2016). This consideration has often been neglected in previous research, resulting in an overestimation that can be addressed using the Bass diffusion model (Fett et al. 2021).

This study employs regional Bass diffusion models to estimate the number of residential battery adopters, addressing the lack of information on the number of adopters and representing the regional characteristics of the system. The regional aspect of the analysis is essential from the system perspective as imbalances caused by the high share of renewables are local problems.

$$N_{r,t} = M_{r,t} \frac{1 - e^{-(p_r + q_r)(t - t_0)}}{1 + \frac{q_r}{p_r} e^{-(p_r + q_r)(t - t_0)}} \tag{5}$$

The model estimates the annual number of residential battery adopters in region *t* ($N_{r,t}$) at the regional level considering the potential population of adopters ($M_{r,t}$) and innovation (p_r) and imitation coefficients (q_r). Since residential batteries are not widespread enough to estimate the innovation and imitation coefficients, we use the number of installations of residential solar PVs as a proxy.

The innovation coefficients are also used to differentiate the number of innovators across regions. The assumed proportion of innovators in the population is 2.5% (Palm 2020, Rogers et al. 2014). We adjust the proportion of innovators in each region based on the relative deviation of the innovation coefficients from the average (e.g. if a region's innovation coefficient is 10% higher than the average, the assumed share of innovators is 2.75%). The imitation coefficients could be used to represent the spatial correlation between neighbouring regions, however, this is not included in the current modelling framework to simplify the calculations. Nevertheless, this prospect opens up the possibility of future model development.

The starting year for the diffusion of residential batteries is set at 2008. The starting year battery deployment is calibrated to meet the installation target of the current support scheme for solar PVs with battery storage. The scheme provides 66% support for more than 15000 solar system projects that must be installed before the end of 2026 (Hungarian Ministry of Energy 2023b).

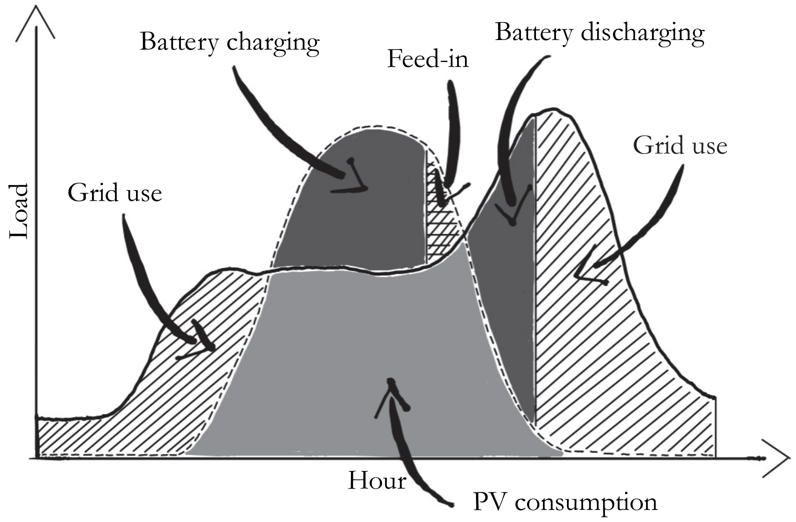
As the potential populations of the Bass models change dynamically from year to year, the hypothetical S-shaped curve of diffusion changes, therefore, each annual model fits the number of residential batteries from the previous year to the S-shape curve corresponding to the actual potential population. We then calculate the additional number of adopters based on this segment of the curve to ensure an S-shaped curve.

Battery charging

Battery charging and discharging patterns are estimated at regional, load profile and consumption size levels. Residential batteries' output is solved continuously every hour of a year. The model does not assume any incentives for prosumers to use batteries to provide flexibility services to the system, therefore, prosumers are assumed to be profit maximising. The batteries' operational strategy follows the strategy defined by Fett et al. (2021). Household electricity demand is primarily met by the generated solar power. If surplus PV generation occurs, it is directed towards charging the battery. If the battery is already at full capacity, the excess power is fed into the grid. In instances where current PV generation does not meet demand, the battery steps in to supply electricity to the household until it is completely discharged. Any remaining demand that is not covered by PV generation or battery discharge is fulfilled by the electricity grid, and no exchange occurs between the battery and the grid. The general operation strategy is illustrated on Figure 1.

Figure 1

Schematic overview of the PV battery operation strategy



Note: the dashed line represents the hourly PV energy produced, and the solid line represents hourly consumption.

Data

We demonstrate the model's capabilities using the Hungarian electricity market as a case sample. The analysis incorporates multiple data sources to accurately represent Hungarian households' circumstances.

The main regional characteristics are summarised in Appendix Table A1, while the main parameters of residential batteries are outlined in Table 1. The analysis focuses on a single battery technology, namely, lithium-ion batteries of varying sizes. Furthermore, we use general, urban and rural household load profiles published by (MVM Group 2023). The proportion of household profiles within a region is determined by the proportion of different residential profiles (HCSO 2023). The model assumes small, medium and large consumption levels. The annual consumption of medium consumers corresponds to the average regional consumption, while small consumers consume 75% and large consumers 150% of the average, 50% of the population are medium consumers and are small and large consumers each make up 25%. The battery sizes assumed for small, medium and large consumers, which are proportional to consumption levels, are 3 kWh, 4 kWh and 6 kWh, respectively. The battery size for the medium usage level was determined using a data-driven approach aiming to maximise the NPV of the battery investment. Battery size is solely dependent on the household's consumption level and is consistent across all scenarios. Projections of battery price changes are obtained from Cole–Karmakar (2023). In Hungary, residential consumers pay a lower electricity tariff for consumption below a certain limit (2523 kWh per year), above which the tariff approximately doubles. Consequently, we calculate the electricity price for each profile on the basis of annual consumption.

The hourly solar PV output by region is obtained from the Photovoltaic Geographical Information System (Joint Research Centre 2023).[1] The data were collected for county seats, assuming that solar profiles are the same across associated regions.

Results and discussion

We next present the results of the simulation model for Hungary. First, we describe the baseline results, encompassing prosumers' investment decisions, battery diffusion and the resulting total output of the installed residential batteries. The baseline scenario does not include support for the installation of residential batteries. We then present several alternative policy scenarios that support the diffusion of residential batteries and demonstrate how these developments can affect investment decisions and system-level results.

Baseline scenario

The baseline scenario helps to explain the general dynamics of the model and serves as a basis for comparison with the policy scenarios as it does not assume any supporting policies.

Table 1

Main model parameters of the NPV calculation

Parameter	Value	Sources
Battery cost (EUR/kWh)	550	Molnár (2023)[a)]
Battery cost relative std. (%)	20	IRENA (2023)[b)]
Depth of discharge (%)	90	Rayit et al. (2021)
Battery efficiency (%)	90	Rayit et al. (2021)
Battery lifetime (year)	15	Rayit et al. (2021)
Discount rate (%)	5	Rayit et al. (2021)
Annual electricity price growth (%)	2	Fett et al. (2019)
Electricity price band limit (kWh)	2,523	Hungarian Government (2022)
Electricity price low band (EUR)	0.0953	Hungarian Government (2022)
Electricity price high band (EUR)	0.1845	Hungarian Government (2022)
Feed-in tariff (EUR)	0.0131	Hungarian Government (2022)
Labour cost of installation (EUR/kWh)	240	Molnár (2023)[a)]

a) Battery cost and installation labour cost reference the total battery cost from Molnár (2023), assuming a 70–30 split.

b) The standard deviation of battery installation is derived from the 5th percentile value and mean of PV project costs in 2022 presented by IRENA (2023).

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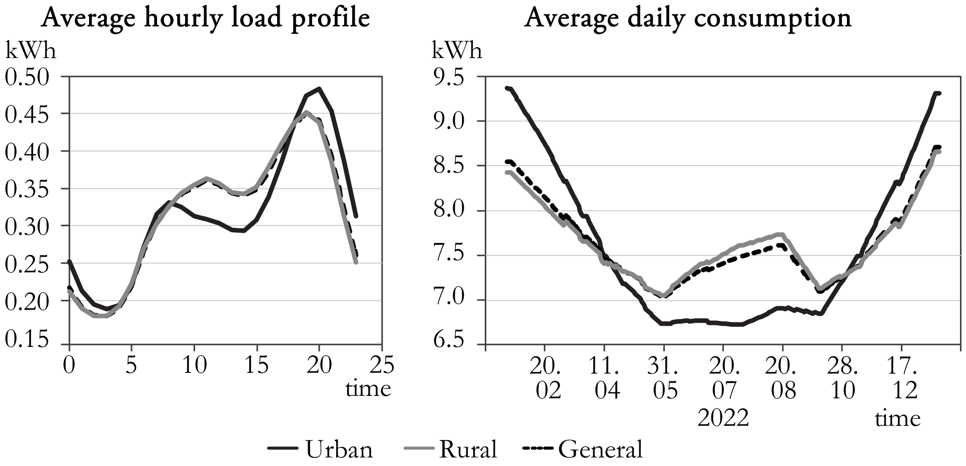
[1] The solar PV output data were collected usaing the parameters of slope = 35°, azimuth = 0°, nominal power of the PV system (c-Si) (kWp) = 1, system losses = 14%.

Prosumer investment simulation

In the model, investment decisions are made by agents with different characteristics. The analysis considers nine agents, consisting of three household load profiles and three consumption levels. The load profiles define households' consumption patterns throughout the year at the hourly level. Figure 2 shows the average daily load pattern and the 4-week rolling average of daily consumption in Pest county.

Figure 2

Average hourly load profiles and 4-week average daily consumption by profile in Pest county



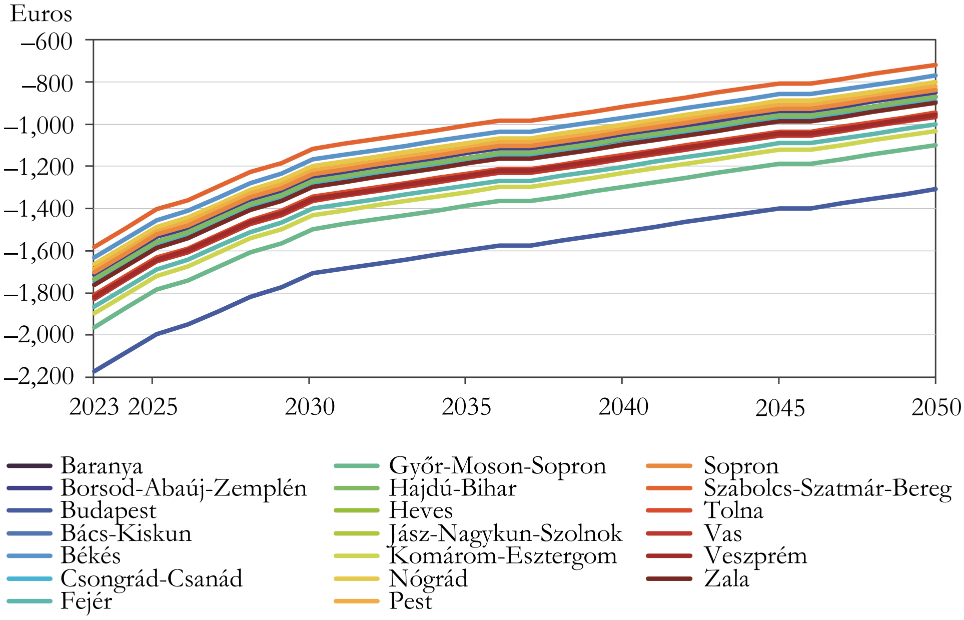
Source: Hungarian Energy and Public Utility Regulatory Authority (2023) and authors' calculation.

All load profiles reveal a significant increase in load from 3 pm, reaching the daily maximum around 8 pm. The load then decreases rapidly until around 4 am, when the morning starts. All load profiles also reach peak daily maximum consumption around the end of December/beginning of January. Although general and rural load profiles are fairly similar within a day, their seasonal patterns of consumption differ more. The general profile exhibits a lower peak during the summer, whereas it is higher during the winter. However, the urban profile has a much higher evening peak compared with the two others, and the seasonal differences are also higher.

The NPV can be calculated based on the load and solar profile to determine the benefits of investing in a battery. Figure 3 illustrates the evolution of NPVs for a general, medium-level profile. While an upwards trend in NPVs is observed due to falling battery prices and rising electricity prices, all values remain negative in 2050, therefore, current electricity prices are insufficient to offset the high initial costs of battery installation, even with a 2% annual growth rate. The NPV values exhibit a consistent trend across all regions, with notable variations, which we primarily attribute to consumption and income levels, although the solar profile also has a significant role. Szabolcs-Szatmár-Bereg county has the highest NPV due to above-average electricity consumption and the lowest average income. Conversely, Budapest has the lowest NPV due to its significantly higher income level compared with other regions.

Figure 3

NPV of battery investment with a general load profile and medium consumption



We introduce the NPVs into the Bass diffusion models to calculate the potential population, establishing benefit distributions based on NPV components and the relative standard deviation of battery installation costs (20%). These distributions, along with the share of innovators, determine the proportion of the total population that may invest in batteries. However, the NPV values are well below zero, indicating that only a small fraction of households would invest in a battery without a subsidy, with the exception of innovators.

Residential battery diffusion

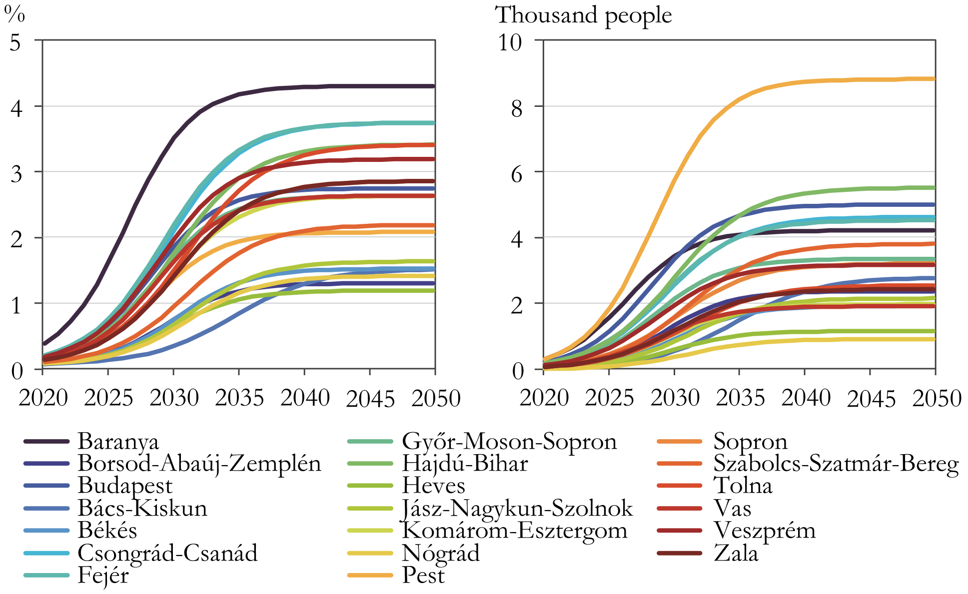
The potential population of the Bass diffusion model depends on the NPV of battery investment to define the maximum number of potential adopters. However, the model does not assume perfectly informed and rational prosumers, therefore, the proportion of the potential population that is projected to invest in batteries in a year is determined using innovation and imitation coefficients.

Figure 4 shows the relative and absolute diffusion of battery owners at the county level. Adoption rates, expressed as the proportion of the total population that is projected to adopt batteries, are marginal in all regions. Throughout the simulation period, only innovators invest in batteries due to the negative NPV of the investment. Therefore, the potential population of battery adopters does not exceed the number of innovators. Regional adoption rates in 2050 range from 1.14% (Heves) to 4.3% (Baranya). We adjust the initial proportion of innovators (set at 2.5%) regionally based on the relative deviation of the innovation coefficients from the national average. The findings reveal that almost all potential adopters will purchase a battery by 2050 and the final adoption rates reflect the share of innovators in the population.

Figure 4

Diffusion of residential batteries by county

Adoption rate Number of residential batteries



In addition, adoption rates almost reach the maximum level by 2040 because most innovators have already purchased batteries by that time, and the high cost of batteries makes installation unprofitable for other households. However, clear differences in the pace of adoption emerge due to varying regional innovation and imitation coefficients in the diffusion model.

The total number of residential batteries in 2030 is estimated to be around 36,800 in 2030, rising to 66,200 in 2050. Regional differences are more pronounced in absolute terms. As there are more than twice as many 1–2 apartment houses in Pest county than in any other region (see Appendix Table A1), the number of battery owners is much higher. This finding emphasises the significance of analysing technology diffusion at a regional level due to the notable differences between regions. Large regions have more potential to introduce batteries and subsequently increase electricity systems' flexibility. Furthermore, these analyses can help policymakers to plan regional grid development appropriately.

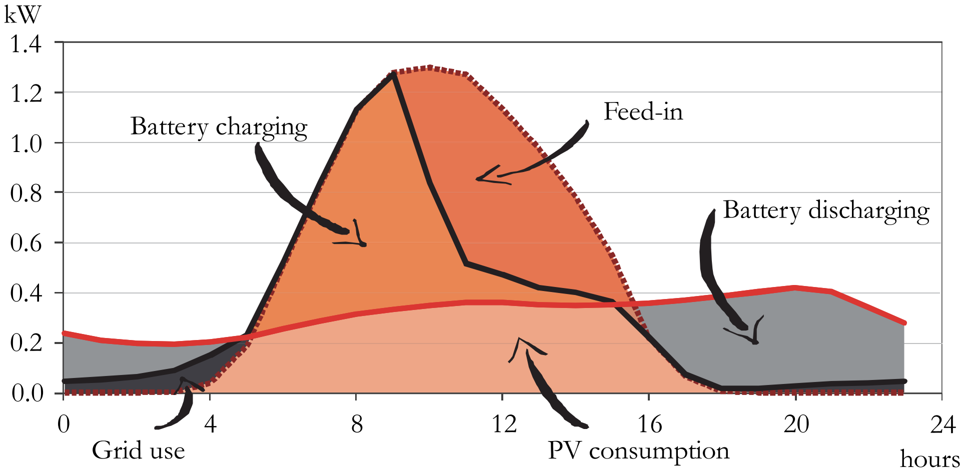
System impacts

Residential batteries installation can have large-scale impact on electricity systems. Batteries store energy when solar power is abundant, which can be used later when other energy sources replace solar power, which is currently dominated by fossil fuel power plants. Batteries help to match households' load on the grid to the available solar power, which reduces the imbalance between electricity overproduction during the day and the peak load in the evening.

Residential batteries remove supply during the day as they are charged and remove load during the evening when they are discharged as the schematic overview of the battery operation in Figure 1 demonstrates. The estimated average PV generation, load profile and battery operation during the summer is presented in Figure 5. Batteries charge when an overproduction of solar energy occurs. At the peak of PV production, batteries are usually fully charged and any excess PV generation is fed into the grid, which aligns with previous literature (Fett et al. 2021). This state is usually reached by around 10 am, after which a sharp increase occurs in the amount of electricity fed into the grid. A charged battery can usually supply a home until midnight, taking the evening load off the grid.

Figure 5

Summer average of a general load profile in Pest county with medium consumption and a battery

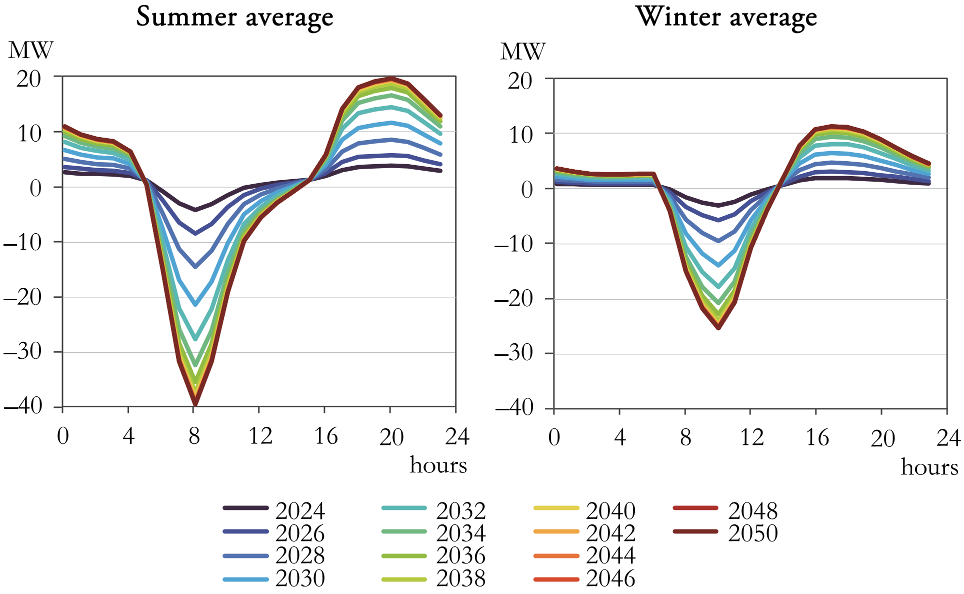


We estimate the overall impact of the batteries on the system by aggregating batteries' output. Figure 6 illustrates the total performance of the batteries averaged over summer and winter. As expected, battery output is much higher in summer than in winter. Solar power generation is much higher during the summer due to longer hours of sunlight that can often fully charge batteries. As shown in Figure 1, batteries take most of the load off the system in the morning hours.

Battery installation exhibits a marginal impact in the early years. However, between 2027 and 2032, the total residential battery storage capacity increases from 87 MWh to 200 MWh. By 2050, the total storage potential exceeds 280 MWh. Peak negative output occurs at around 8 am in the summer when batteries are fully charged, reaching −40 MW. The maximum output, when the batteries are discharged, is at 8 pm, reaching 18 MWh. In winter, the average power is about half of the summer's, ranging from almost −26 MW to 11 MW.

Figure 6

Total output of residential batteries during summer and winter between 2024 and 2050



Note: negative values indicate charging, and positive values indicate discharging.

The baseline results demonstrate that residential batteries will not be widely adopted without policy support and will only marginally contribute to system flexibility. Only 2.4% of the target population will adopt batteries by 2050 without support. Low electricity price and high battery prices discourage households from investing in batteries. Therefore, we next investigate policy scenarios considering different levels and types of subsidies for residential battery installation.

Policy scenarios

We examine four policy scenarios that offer substantial support for households to increase the adoption of residential batteries. These scenarios include two types of subsidies and two ambition levels. The first type is an ad valorem subsidy, in which the government finances a certain percentage of the average installation costs. The second subsidy involves a lump-sum payment to adopters. The first method favours large consumers with high installation costs, whereas the lump-sum payment is more advantageous for small consumers, with the same payment for all profiles and consumption sizes.

Regarding the ambition level, we propose two subsidy packages starting in 2027, one with a budget of EUR 223 million and a more ambitious package with a budget of EUR 840 million. The corresponding subsidy levels are 40% and 50% in the case of the ad valorem subsidy and EUR 635 and EUR 838 in the case of the lump-sum payment. In all four policy scenarios, 66% ad valorem support is assumed between 2024 and 2026, which is consistent with the current support scheme in (Hungarian Ministry of Energy 2023b).

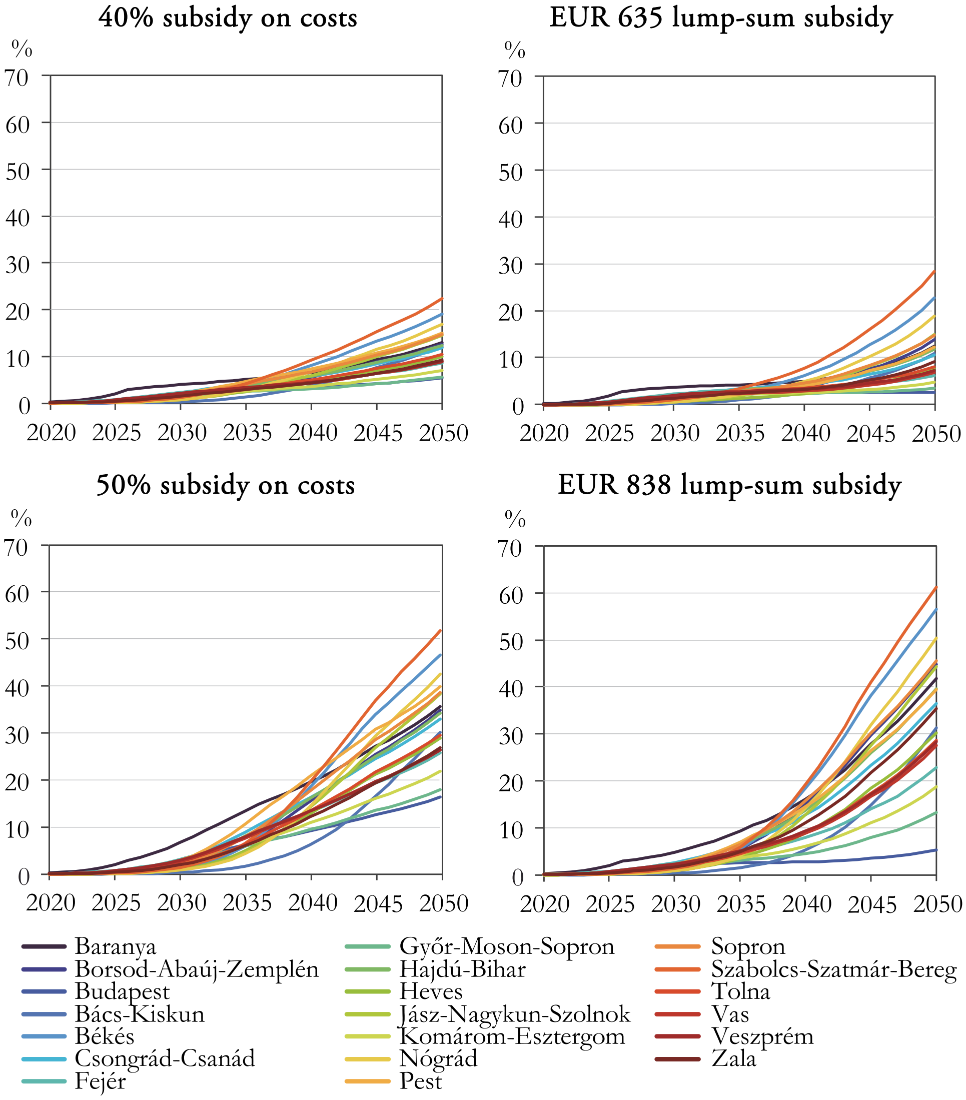
All subsidy packages exhibit substantial impact on households' battery deployment (Figure 7), and more households consider investment in batteries as a profitable choice. Even with the lower budget, the share of battery owners increases almost tenfold. The ad valorem subsidy of 40% is correlated with a total adoption rate of 12.5% (representing almost 350,000 batteries), while the lump-sum payment of 635 EUR reaches 12% by 2050, both with the same total budget of EUR 223 million. In the same year, the more ambitious subsidy packages with an approximately four times bigger budget reaches over a 30% adoption rate (50% scenario: 33.5%, EUR 838 scenario: 35.8%). The lump-sum payment accelerates households' battery installation more in the case of the more ambitious packages. The lump-sum payment of EUR 838 generates almost 64,000 more batteries than with 50% support.

Although the lump-sum appears to be more efficient, regional differences are more pronounced, particularly in the ambitious scenario. The range of adoption rates is 56%, while in the 50% subsidy case it is 35%. The lump-sum payment makes battery investment more profitable in regions with higher NPVs, however, in Budapest, where the NPV is the lowest, diffusion does not notably increase, with an adoption rate of only 5.2%.

Battery diffusion does not exhibit an S-shaped curve in the policy scenarios as the number of batteries continues to grow rapidly even in 2050, which is attributable to the continuous decrease in battery costs, resulting in progressively higher NPVs each year, which subsequently broadens the pool of potential adopters. Despite significant support for battery installation in the ambitious scenarios, some households still initially perceive it to be unprofitable. However, as battery costs diminish over time, these households begin to consider the investment as financially viable, expanding the population of potential adopters. Notably, a second inflection point emerges in multiple counties around 2045 in the ambitious scenarios, indicating slowed growth rate.

Figure 7

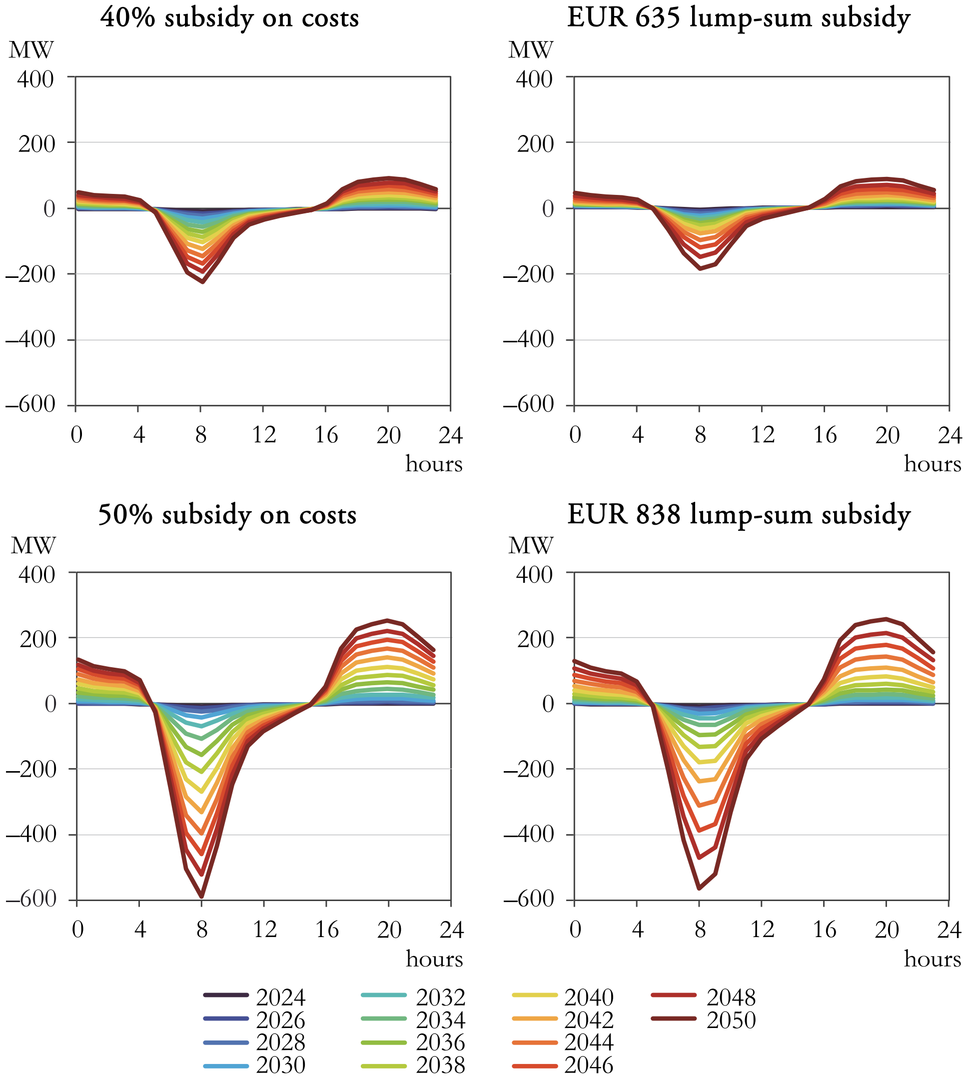
Relative diffusion of residential batteries based on four policy scenarios



Moreover, the outcomes of the baseline and policy scenarios are largely consistent with the findings of Danielis et al. (2023), who combined discrete choice and agent-based modelling to predict rooftop PV and battery storage installations in Italy. The results indicated that without fiscal incentives, the number of households installing solar PVs by 2030 would be minimal, at only 4.9%. This figure represents the proportion of households that would install solar PVs, with approximately 80% of them also installing battery storage. The adoption rate was found to increase to 9% and 94% in the same year, when respective 25% and 75% investment tax credits are assumed to have been in place from 2016 onwards.

Figure 8

Total output of residential batteries during summer



40% subsidy on costs

EUR 635 lump-sum subsidy

50% subsidy on costs

EUR 838 lump-sum subsidy

Note: negative values indicate charging, and positive values indicate discharging.

The average total battery output during summer, shown in Figure 8, illustrates the importance of battery support from a system perspective. While the total battery output is marginal in the baseline case, in the policy scenarios, the load removed during peak hours is substantial. Even in the less ambitious scenarios such as the 40% ad valorem scenario, with more than 1.6 GWh of residential battery storage capacity, the total output ranges from −221 MW to 95 MW. For comparison, the average load in summer 2023 in Hungary is 4470 MW, with an average daily maximum of 5290 MW. In the more ambitious scenarios the range is approximately from −600 MW to 250 MW. Although the number of batteries is higher in the EUR 838 scenario, the total capacity installed is higher in the 50% scenario (3.6 GWh vs. 4.1 GWh, respectively). As the lump-sum payment is a more advantageous incentive for smaller consumers, relatively more 3 kWh batteries are used in the EUR 838 scenario than in the 50% scenario.

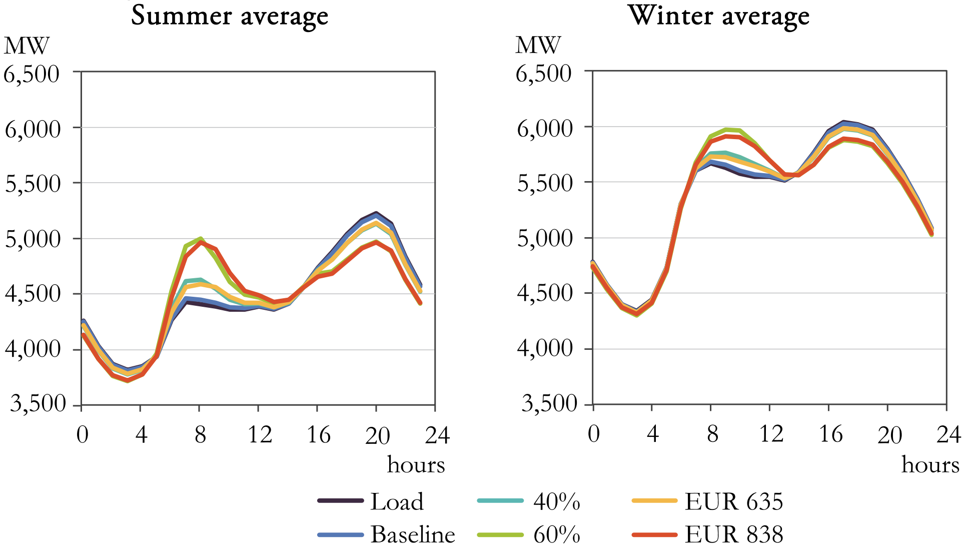
Furthermore, it is also clear from Figures 7 and 8 that a sharp increase still occurs in the uptake of residential batteries even after 2040. Peak output still rises, with 30 MW between 2048 and 2050 in the 50% scenario. Therefore, by providing sufficient support for installation, batteries can be accessible for most potential households and have a significant system-wide impact that can improve the flexibility of the grid.

Finally, we consider system-level impacts relative to the total load in Hungary in 2023, which helps to place the overall impact of the batteries into a real-world context. The average summer load in 2023 was 4470 MW and the average winter load was 5360 MW; therefore, the total output of the residential batteries in the policy scenarios in 2050 is comparable to the total load. However, the timing of charging and discharging is an important consideration from a system perspective. The total load curve and the load curves of the policy scenario adjusted with the corresponding battery power in 2050 are presented in Figure 9. Batteries' charging and discharging essentially shifts the evening peak to the morning hours. This adjustment to the load pattern is a good illustration of how batteries can help to shift the load to the availability of intermittent renewables. The evening peak load in summer (around 8 pm) is 5% lower in EUR 838 and 50% subsidy scenarios. However, in winter, when the total load is much higher, the peak shaving impact of batteries is more modest at 2.5%. This result highlights the importance of long-term storage capacity but is beyond the scope of this study.

The operation of the residential batteries has an enormous influence on system-level impacts. In the current analysis, the model assumes that batteries start charging immediately when there is an oversupply of solar power and discharge when there is not enough to meet demand. However, similar to Fett et al. (2021), different operating strategies could be explored to optimise the use of batteries. Alternative operating strategies could further improve the system benefits of batteries, meaning that the current peak reduction results are likely to underestimate the potential impact of the storage capacities calculated in the policy scenarios.

Figure 9

Total load curve in 2023 and adjusted total load curves in summer and winter, assuming the number of residential batteries in the policy scenarios in 2050



Source: ENTSO-E and authors' calculation.

Conclusions

Energy transition imposes considerable challenges to the electricity grid. An increasing share of intermittent renewable energy sources causes imbalances in the system, therefore, flexibility must be improved. Residential batteries can help to decrease the oversupply of solar energy during the day and shave peak load in the evening.

In this study we presented a novel residential battery diffusion model that estimates the diffusion of batteries considering regional characteristics. The model's capabilities are demonstrated using the Hungarian electricity market as an example. The primary outcome of the modelling exercise indicates that residential batteries will have a limited impact on grid flexibility in the absence of subsidies, and considerable upfront costs are not offset by the comparatively low electricity prices in Hungary. Substantial subsidy support can expedite battery installations and enable significant storage capacities to be established by 2050, however, the manner in which support is provided is crucial. While lump-sum payments result in a higher overall percentage of battery adopters, regional variations are more pronounced compared with proportional support based on installation costs. In addition, lump-sum payments are better incentives for small consumers and ad valorem subsidies are more beneficial for large consumers.

Appendix

Table A1

Summary of regional inputs

County (NUTS3)	Nr. of 1–2 apartment[a]	Net income (HUF)[a]	Electricity consumption (kWh)[a]	Nr. of PVs[b]	Innovation coefficient (p) (10^{-4})[c]	Imitation coefficient (q)[c]
Bács-Kiskun	189,985	292,438	1,902	10,865	0.66	0.306
Baranya	98,863	286,499	1,637	8,126	1.91	0.396
Békés	131,114	255,655	1,759	6,366	0.66	0.371
Borsod-Abaúj-Zemplén	189,557	271,297	1,683	9,417	0.56	0.396
Budapest	184,974	422,052	1,790	14,254	1.21	0.381
Csongrád-Csanád	124,757	294,772	1,754	9,092	1.66	0.341
Fejér	122,058	333,635	1,881	9,363	1.66	0.346
Győr-Moson-Sopron	129,292	357,758	1,834	10,000	1.16	0.376
Hajdú-Bihar	163,536	286,271	1,880	10,104	1.51	0.336
Heves	102,133	314,155	1,930	4,506	0.51	0.391
Jász-Nagykun-Szolnok	136,001	277,126	1,883	4,825	0.71	0.351
Komárom-Esztergom	76,341	337,948	1,969	4,633	1.16	0.356
Nógrád	67,426	265,437	1,993	2,386	0.61	0.361
Pest	433,263	309,942	2,340	32,263	0.91	0.391
Somogy	114,137	275,255	1,570	6,274	1.26	0.341
Szabolcs-Szatmár-Bereg	177,715	241,855	2,009	7,521	0.96	0.341
Tolna	75,709	317,790	1,997	3,912	1.51	0.321
Vas	73,967	313,062	1,750	5,294	1.16	0.371
Veszprém	100,759	307,603	1,624	7,662	1.41	0.361
Zala	86,652	277,055	1,386	4,729	1.26	0.341

Source: a) HCSO (2023), b) Hungarian Energy and Public Utility Regulatory Authority (2023), c) own calculation.

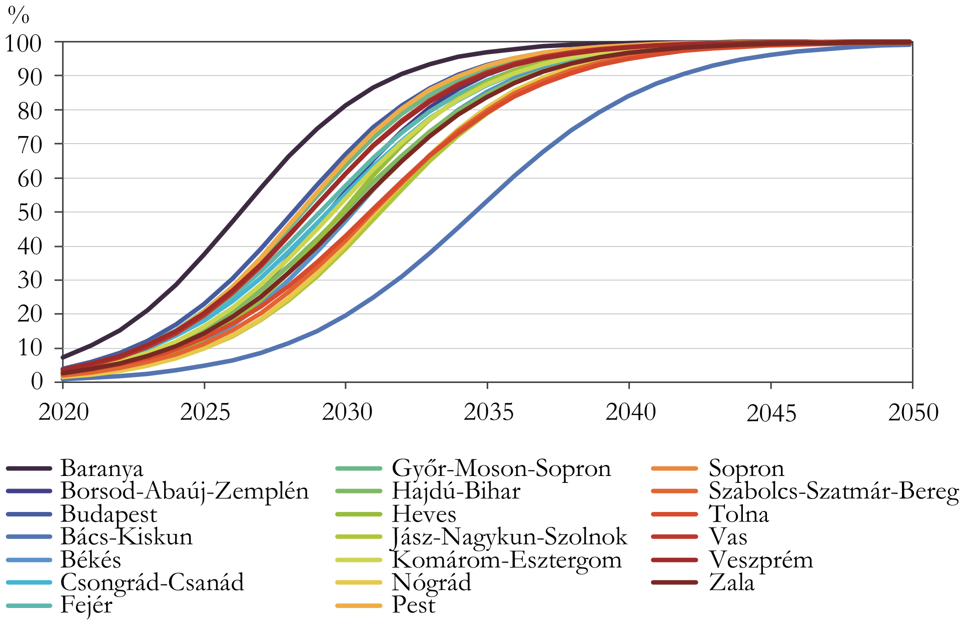
Validation

In order to validate the modelling framework, a scenario is devised which incorporates an implausibly high lump sum subsidy. This guarantees that all households perceive the battery investment as beneficial. This allows for the validation of the dynamics of the Bass diffusion model, as the potential population remains constant throughout the simulation. It is assumed that the subsidy is EUR 10,000, and it is anticipated that almost all households would purchase batteries by the end of the simulation period.

Figure A1 illustrates the relative diffusion of batteries in terms of the number of households under the validation scenario. The S-shaped curves are clearly delineated in the figure, with diffusion reaching close to 100% in almost all counties. This simple test validates the implementation of the Bass diffusion model and demonstrates the necessity of the NPV calculation for modelling the diffusion of residential battery storage. If we had assumed that the potential population of battery adopters was all Hungarian households from the beginning of the simulation period, the estimates would have been too optimistic.

Figure V1

Relative diffusion of residential batteries in the EUR 10,000 validation scenario



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Data availability

Data will be made available on request.

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