One rate does not fit all: An empirical analysis of electricity tariffs for residential microgrids

Gilbert Fridgen, Micha Kahlen, Wolfgang Ketter, Alexander Rieger, Markus Thimmel

FIM Research Center, University of Bayreuth, Wittelsbachererring 10, 95444 Bayreuth, Germany
Rotterdam School of Management, Erasmus University, Burgemeester Oudlaan 50, 3062 PA Rotterdam, The Netherlands
Institute of Energy Economics at the University of Cologne, University of Cologne, Alte Wagenfabrik – Vogelsanger Str. 321a, 50827 Cologne, Germany

HIGHLIGHTS

- We empirically analyze twelve electricity tariffs for residential microgrids.
- We calculate that tariffs with volumetric rates would encourage grid destabilization.
- We show that capacity charges would moderate the impact of time-varying rates.
- We find that a mix of capacity and customer charges would benefit all stakeholders.

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ABSTRACT

Increasingly, residential customers are deploying PV units to lower electricity bills and contribute to a more sustainable use of resources. This selective decentralization of power generation, however, creates significant challenges, because current transmission and distribution grids were designed for centralized power generation and unidirectional flows. Restructuring residential neighborhoods as residential microgrids might solve these problems to an extent, but energy retailers and system operators have yet to identify ways of fitting residential microgrids into the energy value chain. One promising way of doing so is the tailoring of residential microgrid tariffs, as this encourages grid-stabilizing behavior and fairly re-distributes the associated costs. We thus identify a set of twelve tariff candidates and estimate their probable effects on energy bills as well as load and generation profiles. Specifically, we model 100 residential microgrids and simulate how these microgrids might respond to each of the twelve tariffs. Our analyses reveal three important insights. Number one: volumetric tariffs would not only inflate electricity bills but also encourage sharp load and generation peaks, while failing to reliably allocate system costs. Number two: under tariffs with capacity charges, time-varying rates would have little impact on both electricity bills and load and generation peaks. Number three: tariffs that bill system and energy retailer costs via capacity and customer charges respectively would lower electricity bills, foster peak shaving, and facilitate stable cost allocation.

1. Introduction

The microgrid idea mirrors the first self-contained electric systems that existed prior to the advent of utilities [1]. Conceptually, microgrids are interconnected clusters of DG units, electrical loads, and storage units, that can operate both in connection (grid-connected mode) and independent (islanded mode) of the larger macrogird [2]. They facilitate distributed optimization of electricity networks and can improve system reliability, sustainability, and cost-efficiency [3–5]. To date, they have not been widely implemented, yet numerous successful pilots indicate technical feasibility [5–8]. Considerable efforts are still required, however, to integrate microgrids into the energy value chain and to define viable business models [7]. This integration is especially challenging in deregulated energy markets where microgrid operators, energy retailers, and system operators are different entities with diverging economic objectives. Whereas microgrid operators1 effectively aim to secure their energy needs at the lowest possible cost [9], distribution system operators (DSOs) and transmission system operators...
### Nomenclature

#### Indices and model size

- **h**: household index [-]
- **i**: appliance run index. An appliance run can be, for example, a single use of a washing machine or one cooling cycle of a refrigerator [-]
- **H**: total number of households [-]
- **I**: total number of appliance runs [-]
- **T**: total number of periods in the simulation [-]

#### Model variables

- **bc**: overall capacity of all microgrid batteries. Continuous variable (non-negative) [kWh]
- **ci**: total energy used to charge the microgrid’s batteries in period t. Continuous variable (non-negative) [kWh]
- **di**: total energy discharged from the microgrid’s batteries in period t. Continuous variable (non-negative) [kWh]
- **p**: maximum absolute peak over the simulation horizon: maximum amount of electricity that is exchanged with the grid in a single period. Continuous variable [kWh]
- **sgc_t**: solar generation curtailment factor in period t. Continuous variable ∈ [0, 1] [kWh]
- **soc_t**: total state of charge of all microgrid batteries in period t. Continuous variable [kWh]
- **tc**: total electricity costs [USD]
- **wgc_t**: wind generation curtailment factor in period t. Continuous variable ∈ [0, 1] [kWh]
- **x_{h,i,t}**: appliance run activity indicator. Binary variable; one if appliance run i in household h is active in period t [-]
- **y_{h,i,t}**: prevents repetition of an already finished appliance run. Binary variable; one if appliance run i in household h is already finished in period t [-]
- **z_o**: difference between generation and usage if period t is a period of surplus demand; to be weighted with the purchasing price. Continuous variable (non-negative) [kWh]
- **z_n**: difference between generation and usage if period t is a period of surplus generation; to be weighted with the selling price. Continuous variable (non-negative) [kWh]

### Parameters

- **AH_{h,i}**: appliance run to household indicator. Binary variable; one if appliance run i belongs to household h [-]
- **BC**: total capacity of the microgrid’s batteries [kWh]
- **CapC**: capacity charge [USD/kW]
- **CusC_{t}**: customer charge in the respective non-volumetric pricing scenarios [USD]
- **CPR**: critical peak price in period t. This price is only in effect during a system-wide peak and is 0 in all other periods [USD/kWh]
- **FL_{t}**: fixed load in period t. Residual, non-shiftable loads [kWh]
- **FP_{t}**: flat purchasing price in the respective flat and critical peak pricing scenarios [USD/kWh]
- **FSP**: flat selling price [USD/kWh]
- **MCR**: maximum charging rate: physical limit of energy storable in all microgrid batteries in each period t [kWh]
- **MDR**: maximum discharging rate: physical limit of energy accessible from all microgrid batteries in each period t [kWh]
- **PC_{t}**: energy consumed by each appliance run or electric vehicle charging process [kWh]
- **PE_{t}**: processing time of each appliance run or electric vehicle charging process [-]
- **RTP_{t}**: real-time purchasing price in period t in the respective real-time pricing scenarios [USD/kWh]
- **RTSP_{t}**: real-time selling price in period t in the respective real-time pricing scenarios [USD/kWh]
- **RTE**: aggregated round-trip efficiency of the microgrid batteries [-]
- **SG_{t}**: solar energy generated in period t [kWh]
- **SoC_{init}**: total initial state of charge of all microgrid batteries [-]
- **SoC_{min}**: total minimum state-of-charge of all microgrid batteries to avoid undue degradation [kWh]
- **ToUP_{t}**: time-of-use purchasing price in period t in the respective time-of-use pricing scenarios [USD/kWh]
- **ToUSR_{t}**: time-of-use selling price in period t [USD/kWh]
- **UI_{t}**: user preference indicator providing the permissible execution windows for appliances. A value of one states that appliance run i can be scheduled in period t [-]
- **VolC_{t}**: volumetric charge in the respective volumetric and partially volumetric pricing scenarios [USD/kWh]
- **WGen_{t}**: wind energy generated in period t [kWh]

(TSOs) seek to put a cap on the microgrid’s peak loads and fully recover their grid infrastructure investments [10,11]. Similarly, energy retailers are concerned with full cost-recovery and stable load patterns to minimize costs for balancing power [12]. Reconciling all of these vested interests has certainly proven to be difficult [13,14], yet there is reason to believe that tailored electricity tariffs might become the means of choice for linking all players in the microgrid value chain [15–18].

The key challenge to designing effective tariffs for residential microgrids is that common pricing mechanisms for residential customers might not be appropriate for residential microgrids. Feed-in tariff (FiT) mechanisms, for example, offer little incentive for local demand-supply balancing [19], while net metering enforces a single rate for energy purchases and sales [20]. Instead, most microgrid evaluation studies (implicitly) assume, that future policies will stipulate a net purchase and sale approach [14,18,21–26]. This mechanism has the same principal set-up as net metering, but it explicitly permits different prices for times of net load and net generation.

For instance, Speidel et al. [21] evaluate a time-of-use (ToU) tariff that charges for net load, yet does not remunerate net generation. They show that such a tariff could effectively encourage microgrid operators to manage their dependence on external power. In contrast, Atia et al. [22] look at a ToU tariff that also prices net generation. They calculate that both the net generation rate and a sufficiently large range between the highest and the lowest ToU price would be crucial for economic microgrid operation. Several residential microgrid studies also examine demand charges, i.e., charges that price the highest net load peak over the billing period. Hanna et al. [18] and Zheng et al. [23], e.g., look at demand charges with seasonal variation. They estimate that these charges would encourage considerable peak leveling and result in sizeable economic benefits to microgrid operators. Li et al. [24] find similar effects for ToU demand charges that apply only to certain periods, as do Zhang et al. [25] for excess demand charges that apply only to net loads beyond a certain threshold. Ultimately, Sreedharan et al. [26] estimate that demand charges could also encourage microgrid operators to increase self-supply from non-intermittent generation. Meanwhile, Rieger et al. [14] evaluate so-called capacity charges: unlike demand charges, which only price net load peaks, these charges apply to the highest absolute net generation or net load peak. Hence, the authors argue these capacity charges better reflect that residential microgrids can act both as consumers and producers and find them to be highly effective in stabilizing load and generation profiles.

What these studies show is that electricity tariffs can have...
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