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THE PROSUMER-CENTERED APPROACH TO ENERGY MICROGRIDS IN POLAND

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Purpose: This paper presents the application potential of an innovative, prosumer-centered concept of energy microgrids, aimed at increasing benefits for prosumers under the technical and legal conditions of the Polish energy system.
Design/methodology/approach: The concept is implemented through a novel metering and billing system tailored for prosumer microgrids in Poland. It uses a new type of multi-source energy meter, which allowed for maximizing the benefits for prosumers.
Findings: This paper proposes a more prosumer-centered interpretation of the “smart” concept in the context of microgrids operating within the Polish smart grid systems. Traditional smart grid solutions in Poland have focused mainly on balancing and stabilizing energy generation and transmission infrastructure. Existing grid management systems can partially control the prosumer energy use level to enhance balance and stability of utility-scale energy sources and distribution networks -while treating prosumers as secondary, controllable actors. In contrast, the proposed approach directly integrates smart functionalities on the prosumer side, enabling them to gain direct benefits from participating in energy clusters that include renewable energy sources, energy storage systems, and other energy-efficient sources - allowing for lower-cost electricity use. The introduction of multi-source energy meters, which enable the real-time distinction of what portion of the electricity measured comes from specific sources present in the microgrid (e.g., grid, solar, wind, hydro, battery), forms the basis for a new billing method aligned with Polish regulations and technical standards. This enhances the financial viability of microgrids for prosumers and shifts the operational benefits of microgrid participation toward them.
Social implications: The proposed solution supports the development and broader adoption of energy microgrids, especially in prosumer clusters, contributing to energy transition and local sustainability.
Originality/value: The study introduces an original approach using multi-source energy meters as a component of a billing framework designed specifically for Polish prosumer microgrids. This enables a shift in value creation from the utility side to the prosumer side. The concept is relevant to energy cluster and microgrid designers and operators, as well as prosumers engaged in local energy systems.
Keywords: Polish smart microgrids, energy clusters, multi-source energy metering, smart billing system, energy management.
Category of the paper: Technical paper, conceptual paper.

1. Introduction

The escalating requirement to mitigate pollutant emissions is propelling the evolution of power generation systems toward an increased integration of renewable and high-efficiency energy sources within microgrid architectures, complemented by the deployment of advanced measurement and control systems. Energy microgrids in Poland are only beginning to develop, and currently, there are just a few such installations (Adamek, Kordas, 2022; Pyk, 2023; Wasilewski, Kaleta, Baczyński, 2015), which remain largely in pilot or experimental stages. They have not yet reached a level of technological maturity that would enable their broader integration with national power networks and widespread availability for interested consumers or prosumers. Prior studies and analyses aimed at optimizing the operational strategies of electricity generation sources in conjunction with diverse consumer categories (residential, commercial, etc., including clusters of such objects) characterized by distinct load profiles have primarily focused on achieving optimal alignment between the aggregate consumption profile of supplied objects and the overall energy generation profile of interconnected microgrid resources (Shuai et al., 2016; Deng et al., 2023; Attia, 2020). Common approaches include flattening the energy consumption profile within consumer facilities (Chapaloglou et al., 2019; Arcos-Vargas, Lugo, Núñez, 2018), peak-shifting techniques to synchronize consumption peaks with renewable generation peaks (Martinez-Pabon, Eveleigh, Tanju, 2018; Vigna et al., 2018), and predictive load forecasting with a certain lead time to enable adaptive generation scheduling (Li, Wen, Malkawi, 2016; Zheng et al., 2022). All these measures are applied - either individually or in combination - within Polish power networks in general, as well as in smart grids and in the initial implementations of microgrids (Parol, 2024).

A closer examination of these enhancement strategies reveals that their primary advantages are realized from the standpoint of energy generation sources and transmission/distribution networks (Mbungu et al., 2019; Babayomi et al., 2023). It is predominantly the generation facilities and transmission networks that acquire “smart” capabilities, because with the use of dedicated energy management systems they can partially control energy load operations, thereby improving system-wide balancing and operational stability across energy generation, transmission, and distribution systems. Although such improvements can be monetized and theoretically redistributed among participating prosumers (e.g., through reduced unit energy costs), this rarely occurs in practice; end-users typically incur tariffs comparable to those prior to the implementation of microgrid or grid-side enhancements (Charoen et al., 2018; Fridgen et al., 2018; Vergados et al., 2016; Cai et al., 2022).

This study proposes the integration of the smart functionalities on the prosumer side, enabling direct economic and operational benefits resulting from participation in clusters that combine renewable generation units, energy storage systems, and other high-efficiency sources delivering electricity at a lower cost compared to standard grid supply. These benefits are facilitated through the deployment of multi-source energy metering solution, which makes it possible to distinguish what portion of the energy flowing though on individual meter at any given time is supplied from the grid, what from renewable sources, and what from other sources present in the microgrid.

2. Standard metering and billing in prosumer microgrids

Currently, only a few installations in Poland operate as energy microgrids (Adamek, Kordas, 2022; Pyk, 2023; Wasilewski, Kaleta, Baczyński, 2015). These include:

- the Tauron microgrid in Bytom, Poland,
- the PKP Energetyka railway microgrid,
- an industrial microgrid at the WAGO facility near Wrocław, Poland,
- the FOGO microgrid by Generpol,
- the ZKlaster energy cluster microgrid in Zgorzelec, Poland,
- the academic microgrid at Kielce University of Technology, Poland.

None of these networks function as prosumer-based microgrids, which means that the area of prosumer engagement in microgrid investments remains undeveloped in Poland. Similarly, metering and billing systems tailored for prosumer microgrids - specialized and profiled differently from general EMS solutions - have not yet been designed, adapted, or implemented. In traditional microgrid configurations, the operation of individual energy sources is typically governed by the current or forecasted total energy load profile across all consumption nodes. Figure 1 illustrates a representative topology of a prosumer-based microgrid, highlighting the spatial distribution of generation assets and loads, as well as the metering points used for consumer-level billing. Energy delivered to end-users consists of a dynamic mix of energy streams originating from multiple sources, with their respective contributions varying over time according to source availability and current operational status of every source. Conventional meters, measuring the energy consumption by individual consumers at any given moment, however, do not provide differentiation regarding the composition of these flows; they record only the total consumption at a given interval. Consequently, all energy consumed within a billing period is aggregated under a single measurement, and charges are computed based on this undifferentiated total value.

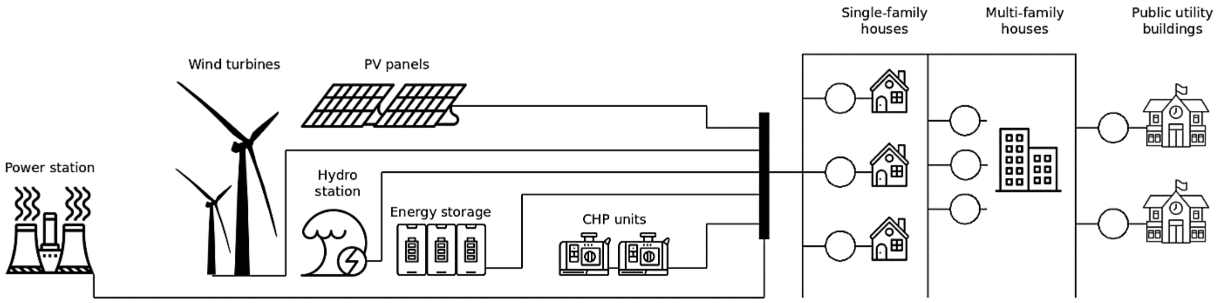

Figure 1. A schematic representation of energy sources and consumption loads within a prosumer-oriented microgrid. The circles indicate individual consumption metering points (with use of standard meters), which serve as the basis for calculating electricity charges for each cluster participant.

The unit energy price within a microgrid cluster is typically set uniformly for all participants, with possible differentiation based on standard tariff structures such as peak and off-peak periods. In practice, this price is established for the current billing cycle or a longer contractual term and remains independent of the proportional contribution of individual energy sources to the total energy consumed. Consequently, scenarios may arise where the cluster's entire demand at a given moment is met exclusively by renewable sources, yet consumer meters still record undifferentiated consumption, which is billed at the general cluster rate per kilowatt-hour. From a consumer perspective, billing should ideally distinguish between energy supplied from the main grid - charged according to the supplier agreement - and energy delivered from renewable sources, which should reflect a lower cost. In clusters incorporating cogeneration units, metering should additionally segregate the share originating from cogeneration systems, applying the corresponding tariff. Current metering and billing systems in prosumer-based microgrids lack this capability, limiting the practical realization of the "smart" concept on the consumer/prosumer side.

3. Multi-Source energy metering

To realize direct cost savings for end-users based on the efficiency of installed energy sources assets within a microgrid, it is essential to implement an advanced metering and billing system capable of recording consumption over defined intervals (e.g., monthly) while disaggregating the energy mix by source - renewable generation, grid supply, cogeneration (where applicable), and other sources. Such the functionality is enabled through multi-source electricity meters, whose architecture and operational principles are detailed in Walek (2023).

As shown in Figure 2a, a conventional meter registers the total aggregate energy flow, representing the sum of all streams from sources connected upstream of the device. In contrast, a multi-source metering configuration (Figure 2b) incorporates additional measurement circuits on each feeder branch corresponding to individual sources. Data from these circuits is transmitted to a central controller, which computes the proportional contribution of each source to the total flow. The controller then relays this information to multi-source meters installed at consumer nodes, enabling separate counters to record consumption by source category. In the example shown, two feeder branches are present - one for grid supply and another aggregating all renewable sources into a single line, based on the assumption that renewable generation uniformly offers a lower energy cost for end-users. The construction of meters supports more than two feeders; for instance, if cogeneration units are integrated, an additional branch with its own power transformer and dedicated counter would be required, as cogeneration typically incurs a cost higher than renewables but lower than grid-supplied electricity.

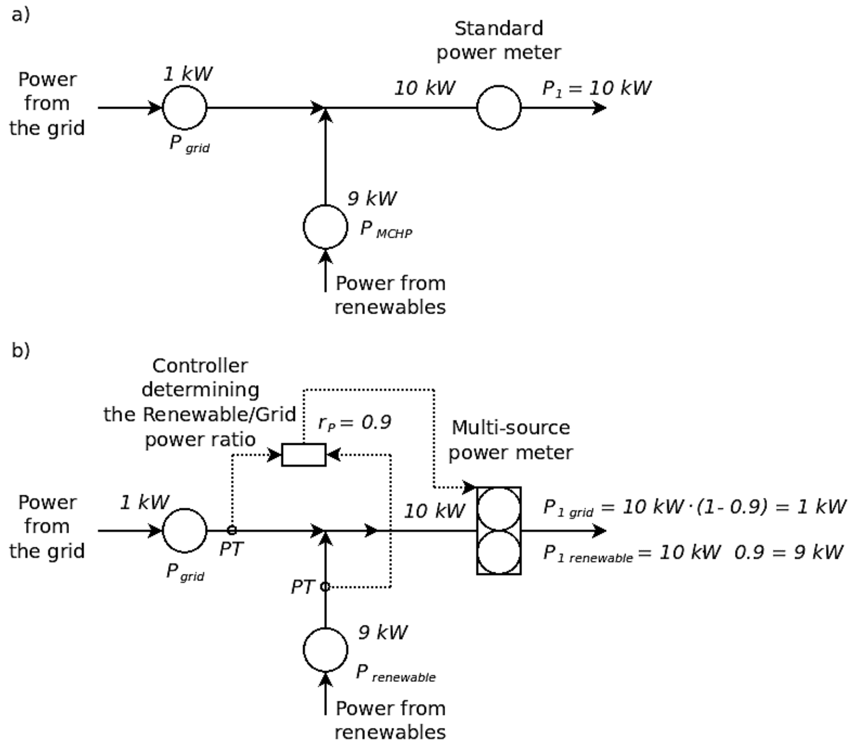

Figure 2. Comparison of energy measurement using a conventional (a) and a multi-source metering system (b). A standard meter records only the aggregate energy flow without distinguishing the origin of supply (grid vs. renewables). In contrast, the multi-source system employs power transformers (PT) on each feeder branch to capture real-time signals from individual sources. These signals are processed by a controller that computes the renewable-to-grid ratio (r_P) and transmits this data to the multi-source meter equipped with separate counters for grid and renewable energy consumed. This enables source-specific energy registration. Displayed power values represent instantaneous readings in kW, while final billing data is expressed in kWh. Solid lines indicate power supply paths; dotted lines denote signal transmission.

For the configuration illustrated in Figure 2b, featuring two feeder lines and two counters within the meter, the control signal generated by the controller and transmitted to the meter would take the form “0.9;0.1” (or, alternatively, a single value such as “0.9,” with the second value derived by subtraction). This indicates, for example:

- r_P = 0.0;1.0 all power at that instant originates from the grid,
- r_P = 0.5;0.5 power supply is evenly split between renewable sources and the grid,
- r_P = 1.0;0.0 all power at that instant is supplied by renewable sources.

For systems incorporating three or more feeders (sources) and corresponding counters, the structure of the control signal would follow the same principle respectively.

4. Multi-Source metering and billing in prosumer microgrids

Figure 3 shows a schematic layout of energy sources and consumption loads within a prosumer microgrid equipped with a multi-source electricity metering system.

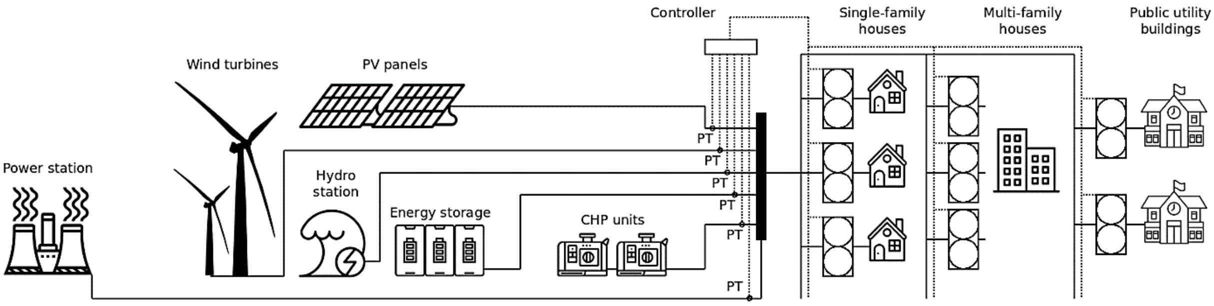

Figure 3. Schematic layout of power sources and consumption loads within a prosumer microgrid implementing a multi-source metering system. This configuration enables source-specific billing for individual cluster members by distinguishing the origin of consumed energy. "PT" denotes power transformers; double circles represent multi-source meters; solid lines indicate power supply paths, while dotted lines correspond to signal transmission.

Each counter within the multi-source meter continuously and separately collects and aggregates real-time consumption data for each of the energy sources. The accumulated values over the billing interval serve as the basis for cost calculation, ensuring that charges reflect the actual amount of energy consumed from each source operating within the cluster.

The unit cost of electricity for each source (or source group) is defined by the cluster operator. For renewable generation, this tariff will be lower than the grid price and reflects associated capital expenditures, operational costs, maintenance, repairs, and lifecycle renovations. The grid energy price corresponds to the contractual rate agreed upon between the cluster and the utility provider. For cogeneration systems, the electricity specific cost can be determined using methodologies such as those outlined in Walek (2023). Any additional service or administrative expenses may be proportionally allocated and incorporated into the source-specific energy cost.

In summary, under a conventional metering and billing framework, prosumer electricity charges for a given billing cycle are calculated according to the relationship:

$$C_{P1}=P_1 \cdot SC_P, \quad (1)$$

where:

C_{P1} - total electricity cost for prosumer No. 1 during a given billing period,

P_1 - total energy consumed by prosumer No. 1 during a given billing period,

SC_P - unit cost of electricity supplied from the microgrid.

The costs for subsequent prosumers are calculated analogously.

In the proposed metering and billing system utilizing multi-source meters, the calculation is expressed as:

$$C_{P1}=P_{1r} \cdot SC_{Pr}+P_{1CHP} \cdot SC_{PCHP}+P_{1grid} \cdot SC_{Pgrid}+\dots, \quad (2)$$

where:

$P_{1\,r}$ - energy from renewable sources consumed by prosumer No. 1 during a given billing period,
$P_{1\,CHP}$ - energy from cogeneration consumed by prosumer No. 1 during a given billing period,
$P_{1\,grid}$ - energy from the grid consumed by prosumer No. 1 during a given billing period,
$SC_{P\,r}$ - unit cost of electricity from renewable sources,
$SC_{P\,CHP}$ - unit cost of electricity from cogeneration,
$SC_{P\,grid}$ - unit cost of electricity purchased from the grid.

The same approach applies to all other prosumers in the cluster.

In a conventional multi-source setup using standard energy meters, billing is limited to applying an averaged unit energy cost across all sources. By contrast, the implementation of multi-source metering enables precise billing based on real-time consumption data, allowing cost allocation that reflects actual source contributions and benefits individual end-users. Both solutions can be implemented under Polish legal and technical conditions. For the variant involving multi-source meters, obtaining appropriate certification and regulatory approvals is required.

5. Discussion

To comprehensively assess the applicability and impact of the proposed metering and billing system in prosumer microgrids, it is necessary to analyze all potential scenarios of energy distribution among sources within the cluster:

- complete coverage of cluster demand by renewable generation, with surplus energy charging storage units,
- partial coverage by renewables and/or storage, supplemented by cogeneration or other systems (if present),
- mixed supply from renewables, storage, and/or cogeneration, with any shortfall met by the grid,
- full coverage of cluster demand by grid supply.

It should be noted that under this model, temporary disparities may occur in the extent to which individual consumers benefit from lower-cost energy.

The proposed solution serves as a mechanism to incentivize investment in renewable and high-efficiency energy technologies within Polish legal and technical frameworks, promoting faster return on investment and reducing electricity costs for prosumers. Furthermore, this approach creates new opportunities for advancing renewable-powered microgrids and accelerating their adoption across diverse consumer clusters. Barriers to the development of such solutions in Poland may include legislative risks that discourage investment, resistance from large energy companies due to their diminishing role in the context of intensive prosumer energy growth, as well as the absence of incentive mechanisms for citizen energy initiatives (legal and tax-related). Additionally, the prevailing focus on individual installations - which do not leverage economies of scale - further limits the expansion of these systems (Wasilewski, Kaleta, Baczyński, 2015).

6. Conclusion

Current enhancements in power grids and microgrids primarily deliver benefits from the perspective of power generation sources and transmission/distribution networks. These infrastructures become “smart” by subsuming (at least partially) consumer-side operations, improving system balancing and stability. This paper extends the smart concept to the prosumer level, enabling direct economic benefits through participation in microgrids integrating renewable sources, energy storage, and other high-efficiency sources that provide electricity at lower costs than grid supply.

This can be achieved by implementing an advanced metering and billing system capable of disaggregating consumption over defined intervals (e.g., monthly) by source - renewables, grid, cogeneration (if present), and others. Existing metering solutions lack this functionality, limiting consumer-side smart capabilities. The proposed multi-source metering system addresses this gap.

Its architecture supports multiple feeder lines from diverse sources, including renewables, storage, grid supply, cogeneration/micro-cogeneration, emergency generators, fuel cells, and additional technologies. The concept can also be adapted for thermal energy (heating/cooling) distribution, subject to further analysis.

This metering and billing approach represents an evolution of the smart grid paradigm for prosumer microgrids, fostering broader adoption of high-efficiency and renewable technologies. It creates new opportunities for the development and scalability of renewable-powered microgrids across heterogeneous consumer clusters. Considering that energy microgrids are only beginning to develop in Poland, it is feasible to implement metering and billing solutions that support prosumer-oriented microgrid configurations, such as those described in this paper. This, in turn, can increase the role of microgrids as a component of distributed and smart energy systems cooperating with conventional generation and transmission networks.

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