Cost allocation in the energy community: a review of tariff design methods in large-scale power systems and their implications on integrated community energy systems

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Abstract

The integrated community energy systems (ICES) transform consumers into prosumers, seeks for self-sufficiency and autonomy, and provides flexibility for large-scale power systems (LSPS). The economic incentive drivers for the rollout of such energy communities, however, the mismatch between long-term investment risk and public-good benefits would encourage free-rider behaviours and destabilize the cooperation. Therefore, the cost and benefit allocation in ICES is essential to provide correct and sufficient incentives for successful implementation. This paper reviews nine regulatory principles and five mainstream methods in LSPS and concludes their implications on ICES. The main design challenges of cost allocation in ICES are addressed including the emergence of prosumers, high penetration of renewable energy sources and collective ownership with numerous small players. Further research efforts are needed to modify the existing tariff design in LSPS and validate it with simulation models or through demonstration projects of ICES.

Keywords: Cost allocation, Integrated community energy systems, Tariff design, Local energy systems, Distributed energy resources

1. Introduction

The emergence of local energy systems around the globe showcases a promising solution towards future power system and sustainable energy transition and [1]. Compared to conventional centralized systems, such bottom-up solutions better integrate distributed energy resources (DER), transform consumers into prosumers for self-sufficiency and autonomy, and provides ancillary services and flexibility for the main market [2]. Several relevant concepts are developed such as Micro-grids, Virtual Power Plants, Energy co-operatives, Peer to peer exchange, Local energy market, Prosumer Community Groups and Integrated community energy systems (ICES) [2, 3].

ICES is defined as a multifaceted, local-level and socio-technical energy system, which is characterized as optimization and integration of diverse DER and storage, multiple energy carriers, demand response, local energy exchange and transactions with neighbouring communities or large-scale power systems (LSPS) [1, 2]. The complexity of ICES inheres within the interdependency and interactions between diverse technological artefacts and numerous decision-making actors such as households, private commercial operators and public regulated parties in LSPS [1, 2]

The economic incentive such as renewable energy sources (RES) subsidy is the main driver for the recent surge of local energy systems, which also holds true for ICES [2, 3]. However, the mismatch between long-term investment risks and public-good benefits would encourage free-rider behaviours and destabilize the cooperation [2]. Therefore, the cost and benefit allocation are essential to provide correct and sufficient incentives for successful implementation. The experience in LSPS could serve as a starting point for ICES. Besides, there is increasing attention on the distribution network tariffs to cope with the penetration of DER and activation of demand response [4]. However, so far as the author's knowledge, there is no such literature that specifically addresses the cost allocation within ICES.

This paper aims to mitigate the knowledge gap in the cost and benefit allocation within ICES by reviewing the status quo and trends in the electricity tariff design in LSPS and concluding their implications when adapted into ICES. The following research question is addressed: what is the design challenges and implications about the cost allocation in the ICES?

The paper is structured as follows. Section 2 introduces the search strategies used to identify cost allocation methods and recent developments. Section 3 presents the existing tariff designs in LSPS in terms of regulatory principles and design methods. Section 4 delves into the cost and benefits within

ICES and elaborates design challenges and implications. Section 5 concludes the main findings of the review and suggests future research directions.

2. Review Methodology

Literature is obtained by searching keywords and using snowballing in Scopus[1]. The used strings are 'network tariff', 'electricity tariff' and 'cost allocation' for the preliminary search in Article title, Abstract and keyword. Then 'micro-grid*', 'local energy system*', 'Distributed generation', 'Demand response' and 'Distributed energy resources' are used to refine the results. The final selection is achieved by two criteria: sorting on the highest citation and filtering the publishing year from 2014. The forward snowballing is targeted at the paper [5] recommended by the research leader, and the same criteria are applied.

Subsequently, 35 studies in English are selected but the most relevant 17 studies are reviewed in this paper. *Fig. 1* illustrates the scoping down of the searching process. Table 5 in the appendix gives an overview of the 17 studies in terms of the author(s), year, emphasis and reference.

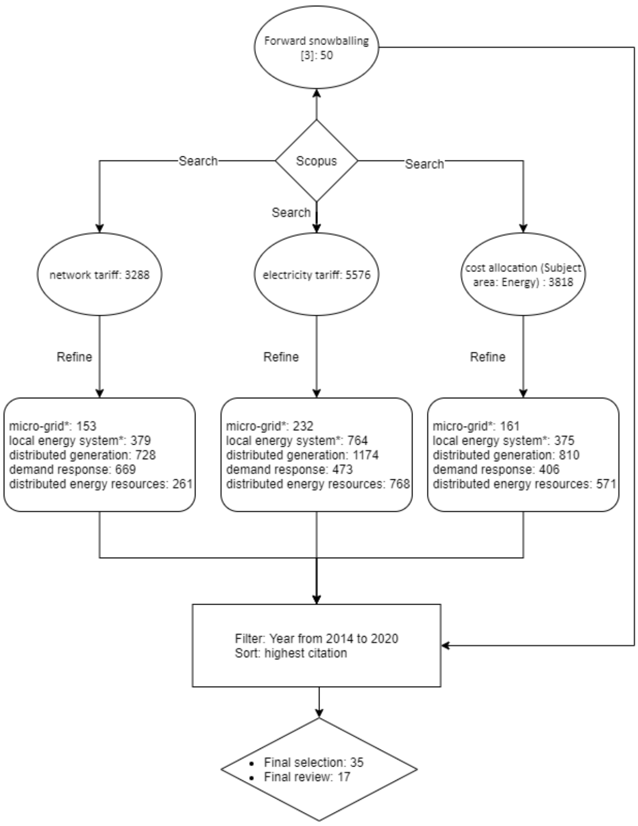

Fig. 1 Searching strategy

[1] Scopus is a source-neutral abstract and citation database with abundant peer-reviewed literature as well as powerful discovery and analytics tools

3. Tariff design in the large-scale power systems

3.1 Regulatory principles for LSPS

A comprehensive tariff design should cover the costs over the whole value chain including electricity generation, energy-related services, network-related service, policy & residual regulated charges [6]. 9 regulatory principles in the tariff design are wildly recognized, namely Economic efficiency, Business sustainability, Equity (non-discrimination), Cost causality, Cost additivity, Transparency, Stability, Simplicity and Consistency, as shown in Table 1 [5-10]. However, those principles are not always harmonious with each other, and thus the unavoidable clashes between principles lead to suboptimal design methods, which will be specified in the next section.

Table 1 Regulatory principles of the tariff design

Principle	Description
Economic efficiency	Provides efficiency economic signals to both production and utilization of electricity; the ideal situation is the use of the marginal cost
Business sustainability	Enable the cost recovery and financial viability, especially for regulated services such as transmission and distribution network and policy costs
Equity	Set the same charges for the same commodity and service despite the purpose of usage and the characteristic of consumers
Cost causality	Allocate the part of costs to the consumer or producer who causes the costs; avoid cross-subsidies
Cost additivity	Sum the rates of each activity into the final tariff (generation + transmission + distribution + retail); comply with the unbundling power sector
Transparency	Inform the users over the whole tariff setting process
Stability	Minimize the unexpected short-term and long-term volatility; provide predictability and mitigate regulatory uncertainty
Simplicity	Formulate a clear and understandable process and method to the users
Consistency	Comply with legal and technical requirements of existing regulations

3.2 Design methods in LSPS

3.2.1 Locational marginal pricing

Theoretically, the locational marginal price (LMP) with adequate temporal and spatial granularity is the optimal method to provide efficient economic signal [5-7]. Such price should capture and reflect both short-term operation conditions and long-term investment needs across time and location in the form of volumetric charge (€/kWh) [7].

However, the existing practices usually simplify the ideal LMP to reduce the computing and implementation complexity. Three simplified forms are ignoring reactive power [7], setting limited time periods (e.g. day/night block and peak/off-peak period [11]), and dividing the power systems into limited geographical zones (e.g. bidding zones in EU [4]). A reasonable tariff design should balance the costs and benefits of granularity. More granularity means improved economic efficiency but more computational, operational and ICT costs [7]. Another fact is that short-term marginal price in general cannot recover the allowed revenue for the regulated activities, therefore, additional adjustments are required to achieve the business sustainability but distort the economic signal [5].

3.2.2 Long-term marginal pricing

Long-term marginal pricing is based on the incremental investment cost of additional demand capacity, which reflects the average cost of the system to guarantee the cost-recovery [5, 6, 12]. Such methods are commonly used for the transmission network such as postage stamp, mean participation factors and contract path [12, 13].

The long-term marginal pricing is easy to implement for the users, however, the estimation of long-term marginal cost still requires complex models and is difficult to check transparently [11]. What's more, the radical uncertainty of network planning and technology development makes it even harder to safeguard the cost recovery, which requires ex-post adjustments [5, 11]. Compared to LMP, there are no short-term operational incentives to improve productive efficiency [9].

3.2.3 Ramsey pricing

Ramsey pricing allocates the part of costs to the consumer based on his price elasticity of demand inversely, i.e. higher tariff is paid by the consumers with a lower price elasticity [11]. This method is targeted at additional adjustments for short-term or long-term marginal pricing in order to minimize the inefficiencies [11, 13].

However, it is rather difficult to decide the price elasticity of each consumer and set different consumer categories especially under the absence of advanced metering infrastructure (AMI) [13]. Meanwhile, such price-elasticity based pricing clashes with the non-discrimination principle. It is hard for low-use or less-off consumers to reduce the electricity for essential service, which indicates a low price elasticity and a higher proportionally tariff against the social welfare [5, 11, 14].

3.2.4 Time-of-use (ToU) pricing

Time-of-use (ToU) pricing sets up various price blocks within a day, compared to flat pricing, which provides a simplified level of the temporal granularity of the ideal LMP [7, 8]. A higher volumetric charge at the peak period could incentive elastic consumers to reduce the peak load or shift that into off-peak period such as through investment in electricity or heat storage [7, 11].

However, the price pattern of ToU still lasts for over one season or one year that is not flexible to the real-time situation [8]. The volume-based ToU pricing also distorts the economical signal for network usage and investment [7]. Other similar methods in distribution network tariff are Critical peak pricing (CPP) and Real-time pricing (RTP). In CPP, the system operator would inform the users of the predictive peak period beforehand, usually in less than one day [8]. RTP reduce the temporal granularity into one hour, which usually couples with wholesale electricity market price and requires the advanced Information and Communications Technology (ICT) services for the consumers [8, 11].

3.2.5 Multi-part tariffs

The Multi-part tariffs are non-linear pricing with a mix of fixed subscription charge, demand charge and volumetric charge [11, 13]. The rationale is to allow different parts to address specific activities in order to improve cost-reflectivity [11]. The demand charge is targeted at the network tariff which is consistent with the fact that almost all the costs of network operator occur from the capacity demand [13]. Such tariff setting allows the differentiation across various cost drivers, such as the voltage level, geographical areas and load profile [5].

However, only 34.6% of European countries applied demand charge in the network tariff that accounts for less than 10% of total income [10]. One reason is that a higher demand charge seems unfair to low energy use consumers and provides perverse incentives for energy-saving [13]. The practice in the Netherlands also shows that an ill-designed demand charge leads to over-contracted capacity and inefficient signal for demand response [10].

Table 2. Tariff design methods and the relations with regulatory principles

	Rationale	Drawback/Limitation	Clashed principles	Reference
Locational marginal pricing	• Classical economic theory • Theoretically optimum to provide an efficient economic signal	• Computing and implementation complexity • Hardly recover the cost of regulated activities	• Business sustainability • Simplicity	[4-7, 11]
Long-term marginal pricing	• Ensure the cost recovery based on the average cost of the system • Easy to implement	• Computing complexity; usually require post-adjustment • Lack of correct short-term operational incentives	• Economic efficiency • Transparency	[5, 6, 9, 11-13]
Ramsey pricing	• Allocate the costs in inverse proportion to price elasticity • Minimize the inefficiency for pose adjustment of marginal pricing	• Hard to decide the utility function • Potential discrimination especially for low-use/less-off users	• Equity	[5, 11, 13, 14]
Time-of-use (ToU) pricing	• Provide economic signal at peak period with a high price • A simplified level of the temporal granularity of the ideal LMP	• Long term price pattern against the real-time situation • Volume-based pricing against the cost-reflectivity of network	• Cost causality • Simplicity (especially for Real-time pricing)	[7, 8, 11]
Multi-part tariffs	• Address specific activities with different parts • Allow differentiation across cost drivers	• Computing and implementation complexity • A high demand charge is unfair for low-use/less-off users	• Simplicity • Equity	[5, 10-13, 15, 16]

3.3 Relations between regulatory principles and design methods in LSPS

Table 2 summarizes the rationale and limitation of the five methods and identify the clashes with the regulatory principles.

It could be observed that economic efficiency versus business sustainability and cost causality versus simplicity are two most clashed pairs. Because the lumpy investment of regulated monopolies implicates deviations from short-term marginal pricing to mitigate the risks of cost-recovery [5, 6, 9]; cost-causality requires the identification of cost drivers and quantification of its impact on system operation costs and investment, which indicates complex modelling and computation [5, 12, 15, 16]. Equity is a relative principle because in some cases intended price discrimination is desired to improve economic efficiency and redistribute wealth [5, 6]. Also, the five methods are not mutually exclusive and it is possible to have a mix of methods integrated into the multi-part tariffs.

4. Cost allocation in the Integrated Community Energy Systems

4.1 Costs and benefits within ICES

The costs of ICES mainly includes five categories: capital cost, fuel cost, operation & maintenance cost, transaction cost and network cost [1]. Table 3 gives a cost overview.

Compared to the LSPS, ICES has extremely low variable costs (Fuel and O&M) due to a high degree of RES penetration; the network costs also reduce dramatically with the proximity of production and consumption. Therefore, the initial investment cost for DER, storage and energy management system takes a dominate share of the total cost.

Table 3 IECS cost overview (Derived from [1])

Type of costs	Description
Capital cost	Initial investment cost for the DER, electrical energy storage (EES) and energy management system (EMS) at both household- and community-level
Fuel cost	The cost of feedstock such as biomass, diesel and natural gas; intermittent generation (PV and wind turbine) has no fule cost
Operation & Maintenance cost	O&M cost for DER, EES and EMS; supply and demand-side management; local energy exchange; local energy-related services, e.g. operating reserve
Transaction cost	The cost associated with formulating contracts and billings within and between the local and main market
Network cost	Interconnection cost between households and communities; local network-related service, e.g. voltage control, power quality, congestion management

On the other hand, four kinds of benefits emerge and should be redistributed within ICES (as shown in Table 4). From the regulatory perspective, there exist financial incentives to support the ICES considering the fact that such local energy initiatives have positive externalities on the society, e.g. reduced energy loss, job creation and sustainability [1]. As for grid-integrated ICES, the power and service exchange with the LSPS could generate revenue and benefits. Those benefits also indicate the cost-savings on the energy and ancillary services for the community vis-à-vis the scenario without ICES.

Table 4 IECS benefit overview (Derived from [1])

Type of benefits	Description
Support incentives	Financial incentives from national/regional support policies such as RES subsidy, tax cut, grant, etc.
Electricity selling	Revenue from trading surplus electricity on the power market
Balancing service to LSPS	ICES provides the operating reserve to mitigate the imbalance and obtains the remuneration.
Other ancillary services to LSPS	Such as voltage control, frequency control, peak shaving, black start capacity, etc.

4.2 Design challenges and implications for ICES

The regulatory principles for tariff design in Table 1 still hold in ICES, however, their importance and emphasis would change accordingly. Considering two envisaged operation model for ICES, the service model introduces professional and dedicated energy service companies (ESCO), which exhibit similar characteristics with actors in LSPS, but the design principles should be applied in a small-/local- scale; in the cooperative model, ESCO could still be responsible for complex operation but the facilities in ICES are collectively owned and controlled by the local community [1]. The introduction of ESCO implicates the possibility of an integrated or partially re-bundling service entity, which weakens the role of cost additivity [1]. Besides, smart household, building, battery and community EMS with AMI allow the access and process of abundant production and consumption data, which empowers the computation and implementation capacity of more granular methods against the simplicity principle [2].

Furthermore, the existing tariff design practices in LSPS are not fully applicable to the ICES. Three design challenges are identified and relevant design implications from LSPS are elaborated below.

4.2.1 From consumer to prosumers

The consumers in LSPS are transformed into prosumers who invest DER in ICES, which enable the demand response, energy efficiency measures and peer-to-peer exchange for self-optimization [1, 2].

Similar issues exist in both LSPA and ICES due to the emerging prosumers, including positive & negative DER externalities, cross-subsidising and DER diversity [3, 12, 16]. Compared to single volumetric charge, fixed charge or demand charge, multi-part tariffs have the advantages to reduce congestion and minimize the current & future system cost with active prosumer response [15, 17]. [16] compares four different settings of multi-part tariffs for distribution network (DN) and concludes that a fixed part for grid connection costs and two variable parts for energy losses and residual costs are optimal under the net-metering mechanism. Such setting not only provides enough incentives to the investment of DER but also reflects DER externalities to the distribution network operator (DSO) to avoid cross-subsidising between non-prosumers and prosumers, which shows the transferability to address the cost allocation between households with diverse investment contribution in ICES. [12] combines the locational marginal pricing within the multi-part tariffs for DN in order to allocate the cost to specific DER. Two algorithms in transmission network (TN), namely Kirschen's tracing and Bialek's tracing, are adapted to quantify the contribution on the network use of each DER, which implicates the feasibility for tailed-made design methods according to the household portforlio in ICES.

The inter-dependency of prosumers and collective ownership of ICES poses more challenges to identify cost causality. The rationale behind cost causality is extended by allocating the benefits to who made the investment [1]. What's more, the public-good characteristic of some facilities and services make it harder to quantify the cost and benefit drivers. Complementary coordination is required to provide correct signal and reduce information asymmetry to avoid over-investment of active prosumers and prevent free-riding behaviours of "passive prosumers" [15].

4.2.2 High penetration of RES

ICES facilitates a high penetration of various RES under the existing RES support scheme and decreasing RES costs. Similarly to the LSPS, RES-dominated portfolio indicates uncontrollable generation intermittency and a potential mismatch between peak generation and demand especially for solar PV [18]. The widely implemented net-metering mechanism under volumetric tariff is criticized by the resulting implicit subsidies to RES owner, and a demand charge could alleviate the unfairness [16, 18]. In addition, net purchasing is feasible in ICES with the installations of AMI. The essential role of EES including electrical vehicles (EV) in providing flexibility requires the specific incentives to simulate optimal response [12].

The high initial costs for RES and complementary EES emphasize the long-term economic signal from cost allocation, which requires a trade-off with real-time incentives for instantaneous response. The interaction with LSPS, namely contribution to the energy- and network- related services, should also be reflected in the bills. What's more, the potential integration of multiple energy carriers from RES exacerbates the complexity of cost allocation and requires coordination with heat/gas bills.

4.2.3 Collective ownership with numerous small players

More importantly, ICES involves numerous small players with densely spatial distribution, and the roles of those players are mixed rather than dedicated in the unbundling LSPS [1, 2]. On the one hand, the emergence of prosumers and re-bundling service providers implicates the internal interactions and transactions of one player, on the other hand, ICES players are also market players in LSPS. Furthermore, the coexistence of private ownership on household-level facilities and collectively ownership on community-level facilities blurs the boundary of cost/benefit drivers.

Within ICES, costs and benefits of more granularity should be evaluated and balanced under the capacity of advanced ICT; the spatial granularity is consistent with prosumers categories in the community-level context, which is still a remaining issue. For each player with mixed roles, it is more challenging to quantify the externality on other players and the system as a whole. Besides the transaction mentioned in Table 4, the positive and negative externalities of ICES on LSPS should also be internalized in the financial settlements between the ICES and LSPS, such as land-use impacts, greenhouse gas emission mitigation, reduction of network investment [7].

5. Discussion and Conclusion

As a modern development of local energy systems, ICES synergizes with sustainable energy transition and the trends of energy autonomy. The economic incentive is the main driver for households to initiate ICES, however, no cost allocation methodology specifically addresses ICES. The study aims to fill this gap by reviewing nine regulatory principles and five mainstream methods of in LSPS and concluding their implications on the design challenges in ICES.

The nine regulatory principles in Table 1 still holds in ICES, however, the roles of cost additivity and simplicity are weakened due to partially re-bundling service providers and widely-used smart EMS & AMI. Three identified design challenges are the emergence of prosumers, high penetration of RES and collective ownership with numerous small players. Compared to single volumetric charge, fixed charge or demand charge, multi-part tariffs showcase the advantages of combining a mix of methods to balance between economic efficiency and business sustainability. A fixed component and demand charge could provide long-term economic signal for lumpy investment of RES, EES & EMS and mitigate cross-subsidizing between households with diverse investment contribution in ICES. Variable components could combine locational marginal pricing to enable short-term incentives for optimal demand response.

No one uniform method of cost allocation will suit all the households with diverse DER portfolio. Sophisticated simulation models enable to trace the contributions of system costs back to each RES, EES, EV and load profile, which empowers the tailor-made and more granular methods together with advanced ICT. From the systematic perspective, it is possible to only formulate a regulatory framework to allow abundant tariff designs for the household to choose what maximizes its utility and thereby improves the overall welfare.

The inherent limitation of the review lies in the early stage of ICES research domain, where most of the literature are conceptual studies with few demonstration projects. The proposed design implications are not backed on empirical practices in ICES. Besides the reviewed mainstream methods in LSPS, some variations or innovative niches could be of interest as well.

Further research efforts are needed to modify the existing tariff design in LSPS and validate the proposed method with simulation models or through demonstration projects of ICES. Prosumer categorization and multi-carrier interaction are two proposed design focuses. Prosumer categorization is consistent with a reasonable granularity to balance cost causality and simplicity. Both technical and social-economic factors should be considered from the voltage level, generation & load profile, contribution on energy/network-related services to the investment portfolio and environmental externalities. As for multi-carrier interaction, potential synergies and clashed when integrating into a multi-carrier cost allocation should be investigated and compared with a dedicated electricity bill.

Acknowledgements

The author would like to thank the course team of SEN131A CoSEM Research Challenges (2019/20 Q4) at Delft University of Technology. It was such a valuable journey from the comprehensive and interactive lectures by Prof. Jolien Ubacht, Prof. Bert van Wee and Dr. Jan Peter Bergen to the patient and enlightening guidance by research team leader Na Li (PhD Candidate) and Prof. Rudi Hakvoort.

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Appendix

Table 5 Overview of selected literature

Author(s)	Year	Study emphasis	Reference
I. Abdelmotteleb et al.	2018	Demand response; evaluate four network charges fixed charge, volumetric charge, peak demand charge, peak coincidence plus fixed charges in terms of system cost and cross-subsidization;	[15]
C. Bergaentzlé et al.	2019	Power to heat & demand response; evaluate three tariff designs in terms of district heating flexibility using electric boiler	[11]
D. Biggar & A. Reeves	2016	Implications for the network tariff methods with the presence of prosumers; compare demand-based tariff and locational marginal pricing	[19]
T. Brown et al.	2015	Evaluate five tariff design methods based on three principles: efficiency, fairness and gradualism including Postage-stamp, Ramsey pricing.	[13]
C. Cambini, G. Soroush	2019	Propose a multi-part tariff structure (fixed and variable components) to mitigate the distortion by the net-metering mechanism for DER	[16]
B. Dupont et al.	2014	A new locational dynamic pricing scheme for emerging centralised and decentralised renewable energy resources	[8]
G. Fridgen et al.	2018	Model and evaluation of the impact of 12 tariff designs for a residential microgrids; mainly categorized as static pricing (e.g. flat, time-of-use), and dynamic pricing (e.g. critical peak, real time).	[17]
F. Hinz et al.	2018	Overview of current tariff mechanisms in 17 ENTSO-E countries; evaluate seven tariff designs and 2025 scenario analysis regarding the challenges with the integrated of DER	[20]
S. Neuteleerset al.	2017	Evaluate the fairness of dynamic tariff designs; propose a normative criteria to assess fairness	[14]
D. Newbery et al.	2018	Review of whole market design for the further electricity power system; six market design principle	[4]
M. Nijhuis et al.	2017	Evaluate cost-reflectivity and predictability of various tariff designs; peak load based network tariff ranks the best	
M. Ortega et al.	2008	Review of distribution network tariff – regulatory principles, methods and rate structure; propose a novel cost-causality-based method	[5]
A. Picciariello et al.	2015	Review of cost allocation methods; issues and challenges due to the integration of DER; a new cost causation-based method is proposed	[9]
A. Picciariello et al.	2015	Combining net metering and pure volumetric tariffs with integration of pv system; Charging mechanism for distributed generation	[21]
J. Reneses et al.[2]	2011	A general tariff design method targeted at the transition economics/developing countries; under the progress of liberalization	[6]
P. Simshauseret al.	2016	Compare and evaluate the peak capacity-based 'demand tariff' and two-part network tariff with the presence of household PV system	[18]
T. Soares et al.	2015	A novel model integrating Locational marginal princes (LMP), two cost-driver tracing algorithms, MW-mile; considering DER, demand response and energy storage system and electric vehicles to grid	[12]

[2] Recommended by the research leader