INVITED PAPER

Data Standardization for Smart Infrastructure in First-Access Electricity Systems

This article focuses on data standardization for electricity access and renewable-energy-based microgrids, since such data would play a significant role in the context of electricity access.

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ABSTRACT | Recent developments in renewable energy and information technology (IT) fields made it easier to set up power systems at a smaller scale. This proved to be a turning point for developing first-access electricity systems for the underserved locations around the world. However, there are planning and operation challenges due to lack of past data on such places. Deployment of Internet-of-Things (IoT) devices and proliferation of smart infrastructures with additional sensors will lead to tremendous opportunities for gathering very useful data. For different stakeholders to access and manage these data, trusted and standardized mechanisms need to be in place. Storing proper data in a well-structured common format allows for collaborative research across disciplines, large-scale analytics, and sharing of algorithms and methodologies, in addition to improved customer service. Data standardization plays a more vital role in the context of electricity access in the underdeveloped countries, where there is no past data on generation or consumption as in utility grids. Data collected in a standard structure, being it for a short period of time, facilitate learning from the past experiences, monitoring the current projects, and delivering better results in the future endeavors. It will result in ways to better assist consumers and help the industry operate more efficiently by sharing data with different stakeholders. It can also enhance competition, thus making electricity accessible faster and to more people. The focus of this article is data standardization for first-access electricity systems, in general, and renewable energy-based microgrids, in particular. Different data sources and ways that the corresponding data can be exploited, technological and capacity constraints for storage of data, political and governance implications, as well as data security and privacy issues, are examined. This article is relevant to different stakeholders, such as investors, public utilities, nongovernmental organizations (NGOs), and communities. Using the data standardization approach developed here, it is possible to create a much-needed first-access electricity system database. This will provide an important resource for project developers and energy companies to assess the potential of a certain unelectrified site, estimating its demand growth in time and establishing universal control systems that can seamlessly communicate with different components.

KEYWORDS | Data systems; IEC 61850; smart-grid communications; standardization in power systems; Sub-Saharan Africa; underserved communities; Universal Access to Electricity

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I. INTRODUCTION

The prohibitive cost of constructing traditional power systems in the developing world is the biggest hurdle to overcome for universal access [1]. Around 20% of the world's population, mostly located in Sub-Saharan Africa, Latin America, and South Asia, cannot enjoy the benefits of electricity. Continuous use of alternative energy resources for cooking and lighting, such as biomass or kerosene, creates larger problems, such as health issues and/or fatal accidents. There is a certain need to bring clean electrical energy to these communities not only for direct benefits of electricity but also for over-arching benefits, such as local economic development, increased literacy, and female empowerment [2]. Traditionally, governments have focused on extending the existing grid for increased electrification rate [3].

This approach only benefits those who are sufficiently close to the grid, while more isolated locations are ignored [4]. Furthermore, the utility grid is known to be notoriously unstable in these countries and connecting more load to it only adds to the problem. The solution has been the innovative stand-alone systems that private companies developed [5], [6]. Since they are fighting an uphill battle against uncertainty of return on investment and subsidized central grid; these systems tend to use more advanced technology, distributed control, and renewable energy-based microgrids.

One of the challenges with these novel and custom-made systems is the duplicability. These small projects are tailor-made for a specific location and a particular context. Scalability is by no means the hallmark of these designs. For instance, dc microgrids deployed in the southern sector of Rwanda have no scalability nor does the company have such a vision [6]. To unleash the full capacity of unelectrified communities for first-access systems, there are two major issues that are related to the collection and analysis of data as follows.

1) *Forecasting Demand:* In contrast to the industrialized world where the demand for electricity can be projected reasonably well into the future, how demand will evolve from the starting point of no demand is not well understood. In other words, it is easy to predict the future when there is ample information about the past and the trends associated with it. It becomes a difficult problem to estimate the demand of a "not-yet-electrified" location since there are no historical data. The problem is compounded by the fact that the evolution of demand is influenced significantly by the way that electricity is provided, such as solar-based microgrids, solar home systems, and grid-connected electricity.
2) *Lack of Standard Data:* Another major barrier is the lack of good data. This not only includes potentials of renewables that are the main source for these standalone power systems but also operation, load, generation, and customer data are not collected and stored in a standard fashion. This makes it extremely difficult to make educated predictions into the future whether it is related to generation capacity or population growth and demographics.

Some companies have realized this gap and started collecting their own operation and customer data. However, this resulted in many small companies collecting their own data in their own unique way. There is no mutual readability, no large database from which to study and extract meaningful results. A more peculiar situation is encountered when a particular company decides to examine its own data after a couple of years of operation. They cannot understand the meanings of variables and their values, as the data collection system was set up several years ago. Lack of standardized approach to data collection and storage renders the collected data "useless."

In order to duplicate and scale first-access energy systems and, thus, accelerate their proliferation, there is an urgent need for standardized data collection and management. This will not only help current operators understand their system and optimize them better but also support future projects, reduce risks, and increase profitability. Only in this way, can the high risks of first-access systems be reduced and investors be more motivated to channel their funds for them. This article is aimed at developing a standardized data collection scheme for smart infrastructure employed in first-access systems. Section II talks about how important data are for increasing the electrification rate rapidly. Section III discusses the value data standardization as nonstandard data collection does more harm than good and does not provide any assistance. Section IV develops a data collection standard in line with operational requirements of first-access systems. Section V showcases the full-system development of a standard data collection system based on IEC 61850 principles. Finally, Section VI discusses the benefits of this standardized approach and draws the conclusions.

II. IMPORTANCE OF DATA FOR PROLIFERATION OF FIRST-ACCESS SYSTEMS IN UNDERSERVED COMMUNITIES

The availability of accurate and reliable data has a major role to play in improving electricity access, both in order to facilitate the deployment of the corresponding energy systems to communities without electricity and also to address the challenges associated with their real-time operation. These can be considered under two main categories as follows:

1) geographical and socioeconomic data that provide relevant information about communities to policymakers, nongovernmental organizations (NGOs), and investors so as to carry out analysis and make decisions on grid expansion or the development of decentralized energy systems;
2) data that can be crucial for the efficient operation of isolated microgrids, such as user behavior, forecasting

for supply and demand, and fast and reliable real-time operational data relevant for low-inertia microgrids.

The significance of such data is discussed in detail in Sections II-A and II-B.

A. Geographical Data and Communities

Investment decisions by electricity utilities or private organizations about solutions that will address the problem of energy access inevitably rely on the presence of appropriate geospatial data that reveal the needs of individual communities as well as various aspects of their socioeconomic behavior.

On the one hand, this helps utilities and governments to prioritize decision-making and also private companies to identify viable investment opportunities. Nevertheless, the presence of such open access detailed data is currently limited, and it is important that appropriate open-access platforms are developed, as this will accelerate the deployment of both on- and off-grid solutions for energy access [7]–[10]. This may include the following.

1) Statistical data for individual regions regarding access to electricity (e.g., number of households without electricity).
2) Economic indices of the population that can demonstrate the viability of a private investment or whether a publicly subsidized scheme will be needed.
3) Data on mobile use, as the latter could be used as a basis for pay as you go schemes.
4) Data on the daily and seasonal load profile of the users, as well as their social behavior, which could be used to investigate the implementation of smart grids and demand-side management schemes. This will be particularly significant in renewable-based isolated microgrids, where the control of the generation side is more limited.
5) Geographical data associated with weather/climate and other geological characteristics that could help assess the implementation of renewable energy sources, such as solar, wind, or hydroelectric power generation.

In addition to connectivity, another important factor that can affect decision-making and investment in the context of energy access is that of quality of service [11], i.e., the extent to which interruptions in the supply or significant fluctuations in voltage and frequency occur. In addition to the data obtained from household surveys, more systematic and accurate data provided from monitoring devices are important. Such data could be used by regulators to assess tariff increases by utilities and also as a means of identifying disparities in the quality of electricity service among different geographical regions and different parts of the population.

B. Microgrids and Operational Data

Microgrids with a significant penetration of renewable energy sources provide a means of addressing the problem of electricity access in remote rural areas [12]–[15]. Nevertheless, there are various challenges associated with their real-time operation that needs to be explicitly addressed, and the presence of appropriate data for monitoring, control, and planning purposes will be very important in this context [16], [17]. We discuss three main aspects of microgrids where such data are significant in the following. These include the implementation of demand-side management schemes, the optimal management of storage devices, and control challenges associated with the low inertia in an isolated microgrid.

1) Demand-Side Management: In a conventional grid, balancing of supply and demand is achieved primarily from the generation side via frequency control mechanisms. In an isolated microgrid, however, where power is provided primarily from renewables, load-side participation and demand-side management schemes have a significant role to play as storage can often be expensive to deploy, with limitations also in its capacity and speed of response. Furthermore, the fluctuations associated with wind generation and the intermittency of solar power render the balancing of supply and demand even more challenging.

The implementation of load-side participation schemes inevitably requires the presence of smart metering devices as well as appropriate real-time monitoring of the voltage and frequency of the microgrid. The scheme itself can then be implemented in a centralized way, whereby a central controller adjusts the power consumption of non-critical loads or resorts to load shedding in case of emergencies. Alternatively, such a scheme could also be implemented in a decentralized way, whereby various loads respond automatically when significant fluctuations in grid voltage and frequency occur. The viability of such schemes has already been reported in the literature, in both practical and theoretical studies [18]–[20], and thus provides an important mechanism for improving the efficiency and performance of energy access systems.

It should also be noted that data about the social behavior of communities could be important in the implementation of such schemes, as they could allow to classify various types of loads as critical or non-critical and also understand the flexibility that can be demonstrated by users in their energy consumption.

2) Optimal Dispatch of Storage Devices: Storage devices, such as battery energy storage systems, are a major tool that can facilitate the operation of a microgrid helping to address the unpredictability of renewable energy sources and the fact that the generation profile does not always match that of the network demand [21], [22]. Such devices can be used for both primary voltage and frequency control and therefore enhance significantly the operation of the network. To reduce roundtrip losses in energy storage, it is important that the available resources from storage devices are optimally exploited by means of appropriate dispatch strategies [23], [24]. In order, for this, to be achieved forecasting, data are needed for the generation and demand as well as real-time monitoring of the state of charge (SOC) of each of the devices.

3) Low-Inertia Microgrids and Control Challenges: The inertia of synchronous generators has a major stabilizing effect in conventional power networks, as it enables generators to respond to deviations in demand at very fast timescales due to their own physical rotating dynamics. In isolated microgrids comprised primarily of renewable energy sources, this inertia is lacking, and therefore, system stability and tight control of voltage and frequency become more challenging [25], [26]. In particular, power converters now have a grid forming role rather than just being grid following ones, as they need to synchronize and set the voltage and frequency at prescribed values. The nontriviality of this task lies in the fact that due to the lack of inertia, control systems need to respond at very fast timescales. Therefore, any measurements used within the control policy, such as current, voltage, and frequency, need to be fast and accurate, and also any delays incurred due to the data processing associated with the control mechanism need to be kept to a minimum.

III. VALUE OF DATA STANDARDIZATION

Data are often labeled as exhaust, Web-based, or sensing data. Crowdsourcing is another source of data that can be considered as a category of its own. Some relevant sources of data include smart meters (SMs), sensor networks, customer payment information and credit histories, Web server logs, cell phone call detail records, and satellite imagery. It is not surprising that researchers as well as private and public energy companies are turning to the idea of leveraging data-driven models for performance optimization and improved service delivery [27]. Advanced data analytics provide estimation, predication, diagnostics, and prognostics conclusions from historical and real-time data flows. As more data become available to utilities over time, the algorithms provide more refined insights on grid strategic and operation planning. Data are also of importance to the social sector and NGOs. The coming years will no doubt see the continued growth in data-driven nonprofits and social businesses as the dropping cost of technology makes collecting and utilizing data far more affordable and easier. However, variability in formats, spatiotemporal granularity, access methods, and differing semantic definitions hinder attempts to access, analyze, interpret, compare, and combine data sets.

Additionally, control and optimization techniques and algorithms play a decisive role in energy systems. In fact, using real data in energy optimization and control represents a crucial issue in smart-grid/microgrids' energy flow, renewable energy, and electrical and hybrid vehicles, as well as in energy storage devices. The characteristics of the data are model and application dependent. In this section, we address the different analytical models that benefit from the standardized data, including consumption pattern, customer profiles, renewable sources supply profile, weather data, and pricing schemes, among others. Data-driven models for electrification range from strategic to operational levels, such as planning analysis, forecasting and prediction, monitoring and evaluation, as well as development of new business models to come up with new services. Based on these models, a standard is proposed that includes standard information models and exchange formats to allow consistent and accurate aggregation of information across locations and data custodians.

1) Strategic Planning: Over a billion, people from the bottom of the pyramid currently lack proper access to sustainable energy services [28]. In these contexts, distributed renewable energy systems emerge as a possible solution to provide small-scale and locally based electricity. To reach universal access to electrical power, planning and evaluating energy options for meeting present and future electricity demand are crucial.

Due to the important investment costs of creating a renewable energy structure, a key component in the design and long-term planning of energy systems is to select the best alternative among the different renewable energy systems [29], [30]. Community-scale renewable energy systems' planning is an important problem consisting of justifying the allocation patterns of energy resources and services, formulation of local policies regarding energy consumption, economic development and energy structure, and analysis of interactions among economic cost, system reliability, and energy-supply security.

In order to make such decisions, one needs to consider the prices of generated electricity, greenhouse gas emissions during the full life cycle of the technology, availability of renewable sources, weather data, efficiency of energy conversion, land requirements, and long-term forecasts related to demand and supply. Standardized data sets can help not only describe the characteristics of regions targeted for energy expansion, by offering more detailed energy access data from satellite images, deriving customers' creditworthiness scores from mobile payment history, and indicating user's mobility and urbanization trends from call detail records, but also standardized data allow one to make predictions about future energy demand that, in turn, can be used to optimally select appropriate energy sources' alternatives and tailored pricing models for these regions.

2) Operational Planning: Distributed energy resources (DERs), including energy storage, make timely information more important at the operational level. Several methods that control the operation of DER to optimize energy services require data to perform properly. In this context, analytic models are used to define scheduling of the appliances, power supply resources, storage units over typically one day to one-week horizon with 1 h or tens of minutes discretization [31]. For example, the electric energy price varies over time and the user may receive a reward from an energy aggregator if he/she modifies his/her consumption profile during certain time intervals. The problem is to schedule the operation of the appliances/devices considering different sources of data from overall costs, weather data, and demand. On the other hand, the operation and scheduling of generation and storage units to determine the most convenient combination of technology selection and size are very important when the grid is dependent on intermittent energy resources. This is especially true when dealing with location, selection, sizing, and unit commitment of energy storage.

Another aspect of operational data is that all electricity devices require periodical maintenance. Maintenance in electricity systems is a source of large costs. In integrated systems, the maintenance of DER components is performed based on the data being collected from these devices which are fed into analytical models for optimal maintenance schedules and assessment. The availability of high-resolution/high-volume data, due to the proliferation of intelligent electronic devices (IEDs) in smart grids, paves the ground to implement more accurate and intelligent fault location methods.

There are different applications where the higher temporal resolution of data is needed for operational controls that happen in microseconds or milliseconds. For instance, the detailed data exchange about renewable energy availability is utilized to achieve the short-term balance between power generation and demand [32]. The control model adjusts the output of power generators by measuring power supply–demand balance, reflected by the system frequency and voltage. Depending on the renewable energy availability extracted from the measured data, necessary dispatch instructions are sent. In addition, such data can be utilized to coordinate electric vehicle (EV) charging with renewable energy availability and the load profile to maximize renewable energy capture [33]. It is shown that more frequent data exchange increases obtained welfare. There are other implementations where more high-resolution data are required for proper operations' planning, such as re-synchronization of microgrids [34], protection coordination with high renewable energy penetration [35], [36], and filtering sound data from false data packets [37].

3) Business Models: The emergence of new business models and services will increase the importance of sharing energy usage information and make energy more affordable [38]. In particular, with energy access, customized service for each user can be achieved by modeling which pricing scheme best meets their needs and ability to pay, size of a subsidy, how to price expected future consumption, and which response to expect for a given price differential. On the other hand, prepaid service offers flexibility in payment schedules, allowing customers with irregular income patterns to pay for what they use when they have the resources. In addition, a prepaid service can also increase energy conservation by making the user more aware of the actual cost of energy and of the pace of electricity consumption. Additionally, consumers could make better decisions about emerging energy conservation/efficiency applications, including whether to change demand-response plans or to take specific actions now in anticipation of future events based on up-to-date energy prices and data related to supply and demand. Unfortunately, today, there is limited provision to share electricity usage information directly with the residential, commercial, and industrial consumer. For demand response models and energy management systems to be feasible, data should be collected and shared to identify key electricity services, customer segments, and revenue streams.

IV. STANDARDIZATION OF DATA COLLECTION ON THE BASIS OF OPERATIONAL REQUIREMENTS

In this section, we provide the high-level requirements for data collection standardization in first energy access systems. This section forms the basis for the deeper device-level specific analysis undertaken in Section V. To identify the requirements, we first assess the current practices of metering and data acquisition in field operation from a practical viewpoint. Second, we identify the data requirements that stem from the real-world operation. Third, we present a high-level data standardization proposal for data aggregation of various granularities of both the temporal and the regional coverage.

A. Metering and Data Acquisition Practices

Data acquisition in first-access energy systems goes far beyond traditional mono-directional supply metering. This is because the typically used semiconductor-based energy controllers are flexible in supporting a certain type of desirable business model. These controllers inherently have the capability for taking measurements and to process them. Additionally, data connectivity is often required for these controllers, for example, to realize the integration with mobile money providers. The ability to acquire, process, and transmit additional data can, therefore, be achieved with minimal additional hardware and at a very low operational expense.

To substantiate this claim, we examine the case of the swarm microgrid, as deployed in Bangladesh [39], [40]. This example is particularly representative because of its diversity of components within the energy access system. The swarm microgrid enables peer-to-peer energy exchange between the swarm nodes. Each swarm node incorporates a solar home or similar system, which was largely operated in the stand-alone mode prior to integration in the microgrid. As shown in Fig. 1, solar home systems include a solar PV module, local loads, and a battery. Power flows between these three elements are managed with a charge controller. The integration of the solar home system into the swarm microgrid is accomplished by the

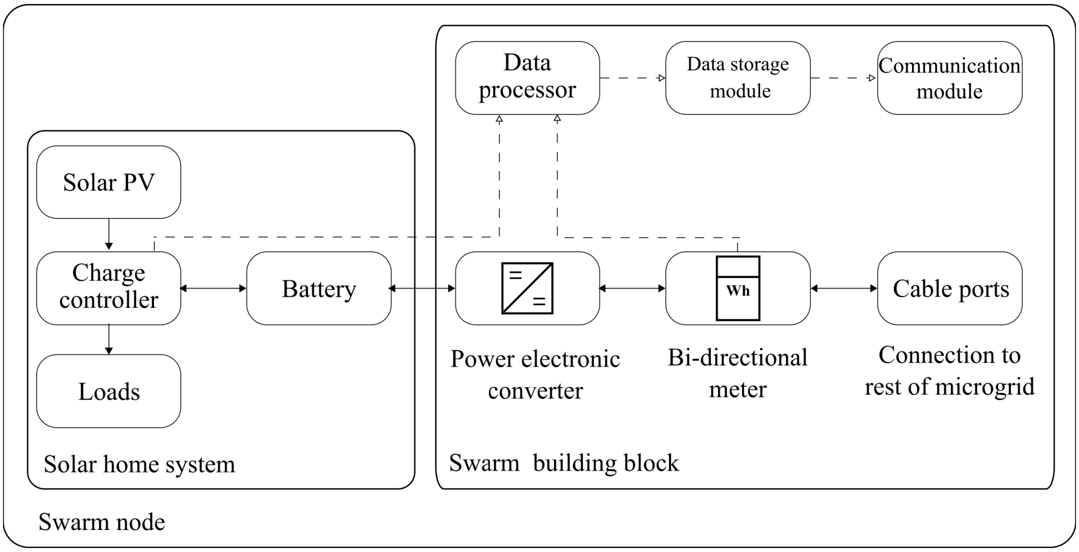


Fig. 1. *Components of microgrid swarm node with distributed storage and generation.*

creation of the so-called swarm building block. A swarm building block in essence consists of a power electronic converter, a bi-directional meter, and cable ports to achieve network connectivity with the remainder of the microgrid. All those components belong to the power hardware layer.

This power hardware layer inherently has a number of sensors built in to measure power flows, both in the charge controller as well as the bi-directional meter. A few additional components are required to take advantage of this data hardware layer to achieve a comprehensive functionality of data collection. These required additional components are a data processor, a data storage module, and a communication module. The data processor is required to enable aggregation and basic analysis of data prior to storage and transmission. Data storage is necessary to buffer data between the stages of processing and transmission. The communication module uses a telecommunication link, typically a GSM network, to transmit the data to a remote server. All the above-mentioned components can be integrated into a single device, as shown in Fig. 1 [41].

Fig. 2 shows the data points acquired from such an integrated device for the time span of 24 h for a day in August; the sample was provided by a P2P microgrid company in Bangladesh [42], but with deactivated data buffering, is shown. The data-buffering functionality had been deactivated to illustrate the following points. It can be seen that in particular, in the period of 21–24 h, there are a number of larger intervals between the data points. These large intervals were due to an unreliable communication link, which prohibited data to be sent right after data sampling and processing. The volatility of the telecommunication link is a challenge in many locations where first energy access systems are installed. This underlines the need for adequate data buffering and appropriate selection of the data to be sent. In this context, appropriateness of the selection means that the data still are to be meaningful and valuable even if its transmission is delayed for a longer time period.

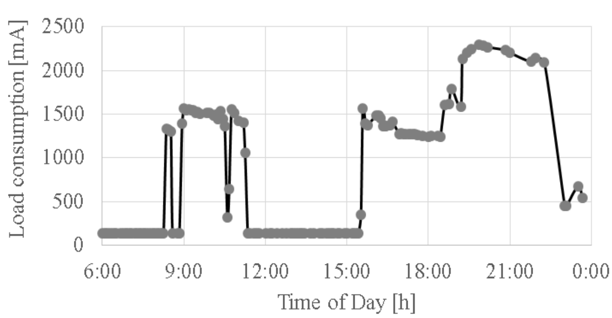


Fig. 2. *Exemplary data without data buffering.*

B. Data Requirements That Stem From Real-World Operation

Building on the data acquisition potential described, we derive the basic requirements for data standardization. Taking an operational point of view, we assess which criteria need to be met by a data standard for first energy access systems. First, all data samples should be clearly and unambiguously identifiable. It must be clear who provided the data sample and which location and time interval the sample provides data for. Second, data security must be respected, which means that privacy rights during transmission, storage, and accessibility must be respected. In addition, it must be clear how the data can be used and if royalties or fees must be paid.

Third, the accuracy of the data set must be clearly stated. This must include the overall accuracy of the data sample, including measurement and processing steps. Fourth, the data sample standard must be scalable to be suitable for different levels of aggregation, which means that the standard should be used for data samples covering individual users across a short period of times as well as for samples covering a large number of users over long periods of time. Finally, the data sample must be compact to be sent with a low-bandwidth communication link and focus on those quantities most important for operational decision-making needs. For this, a clear distinction should be made between the data that are useful for technical monitoring of systems and data that are required to guide more long-term decision-making processes. The latter should be the focus of a high-level standard as it is the case here. The sample must, therefore, focus on those quantities that are required to support a process of informed decision-making regarding investments in additional generation and storage assets as well as into the distribution network.

In summary, the following criteria can be derived for a high-level standardization of such data.

1) *Integrity:* The provider of the data as well as place and time of sampling must be unambiguous.
2) *Security:* The data must comply with the relevant data privacy rights, including transmission, storage, access, and usage rights.
3) *Accuracy:* The data provided must fulfill a predefined level of accuracy.
4) *Scalability:* The standard must allow for different levels of aggregation across time and number of nodes or area covered.
5) *Efficiency:* The data must be compact to be sent with a low-bandwidth communication link and focus only on those quantities required to support decision-making regarding investments.

Against these criteria, a data standard proposal is derived in Section IV-C.

C. Proposed Data Standard

Building on the criteria acquired earlier, a proposal for a data standard is derived and a sample is provided for public use in [42]. The general structure is presented in Table 1. Table 1 is divided into two parts, meta data and energy data. The section containing meta data provides all relevant information to comply with the first three criteria 1)–3). Integrity is achieved by naming the identity of the provider as well as the sample location and sample time. Security is achieved by providing all legal information relevant to data privacy, copyrights, and usage rights. The standard includes different dimensions of granularity in terms of space and time. As such, data samples that are aggregated over many customers and larger time spans can also be made public, without conflicting with data privacy regulations. Accuracy is achieved by stating the granularity, time resolution, and measurement accuracy of the data sample.

The section containing energy data is targeted at fulfilling criteria 4) and 5), scalability and efficiency. Scalability is achieved because all quantities selected can be accumulated over time and over a number of nodes. As such, the aggregated data are always meaningful even if the time span or the number of nodes covered is very large.

Table 1 Proposal for Data Standard of Aggregated Data Samples

Meta data	
Data point	***Explanation, [Unit]***
Identity of data provider	Name, address, contact
Sample location	Country, region, place
Sample date	Date and time at end of sample, [dd-mm-yyyy]
Legal information	Copyrights and usage rights and statement on compliance with data privacy rights
Level of granularity - area	[m²]
Level of granularity - service delivery	Number of nodes, []
Level of granularity - time span covered	[h]
Time resolution of measurement	[h]
Measurement accuracy	[%]
Energy data	
Data point	***[Unit]***
Generation at nodes	[Wh]
Load consumption at nodes	[Wh]
Storage charge at nodes	[Wh]
Storage discharge at nodes	[Wh]
Battery SOC first quartile	[%]
Battery SOC-mean	[%]
Battery SOC-third quartile	[%]
Supply to nodes	[Wh]
Feed-in at nodes	[Wh]

Efficiency is achieved by focusing entirely on those quantities relevant to business-level decision-making. The first two quantities, generation at nodes and load consumption at nodes, reflect the overall supply and demand situation. These two quantities are essential to guide decision-making for investment in additional generation capacity.

The next two quantities, storage charge at nodes and storage discharge at nodes, reflect the role of storage in the energy system and the efficiency of the storage devices. In addition, three statistical quantities for the SOC of the battery are included: the first quartile, the median, and the third quartile. These are used to reflect on the degree of cycling and deep discharge events that batteries are exposed to. Combined with the storage charge and discharge, these quantities are essential to guide the decision-making process for investments in additional storage capacity.

The last two values, supply to nodes and feed-in at nodes, reflect the role of the distribution network in the energy system and the distribution losses. These data points are essential to guide the decision-making process for investments into the distribution network.

Based on the standard developed, we undertake a more detailed, device-level specific, analysis of data standardization in such systems in Section V.

V. STANDARDIZATION OF DATA FLOW WITH IEC 61850

For standardization of data collection in power systems, a standardized information model providing syntax, semantics, and structure of data communicated is required. In the literature, different standards have been proposed for power system data exchanges. Most of these standards are confined to any particular domain or application. The IEC 61850 standard series for power utility automation is the most promising solution since it proposes an object-oriented communication approach for all the components/domains of power system [43].

This IEC 61850 object-oriented modeling approach for power system devices helps to organize data, configure objects, and map them on to protocols so that they are consistent and interoperable. This is achieved since all models follow the IEC Common Information Model (CIM). Because of this flexible yet robust modeling style, IEC 61850 is becoming more popular and being adopted world over as a global standard for power system automation.

A lot of research on the IEC 61850-based automation in different domains of the power system has been reported [35], [44]–[50]. Hence, in this article, the IEC 61850 standard is chosen for the standardization of data for first-access electricity systems. The different components of first-access electricity systems are modeled as per the IEC 61850 standard semantics.

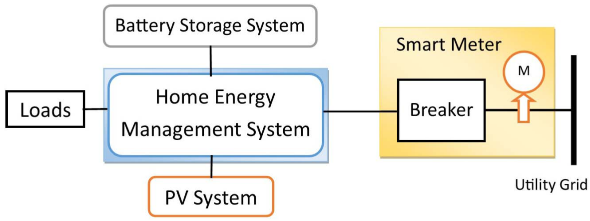
The IEC 61850 information model of different components of first-access electricity systems is developed. Information modeling is a well-established and effective method for managing information exchanges. In the IEC 61850 standard, the group of data objects (DOs) that serve specific functions is defined as logical nodes (LNs) and the composition of relevant LNs for providing the information needed for a particular device is defined as the logical device. An IED may comprise of one or more logical devices. Hence, information models comprising of different LNs are developed for all the components of first-access electricity systems.

There are two major solutions used for first-access systems, solar home systems and microgrids, as shown in Fig. 3(a) and (b), respectively. Components of solar home systems are, as shown in Fig. 3(a), are PV system, home energy management system (HEMS), battery storage system, SM, and loads. Fig. 3(b) shows that microgrids may have more generators, such as wind turbine, biomass chamber or run-off-river hydro, a central energy management system (CEMS), and individual houses. Houses can follow the design in Fig. 3(a) and models for nonexistent components can be omitted, e.g., battery.

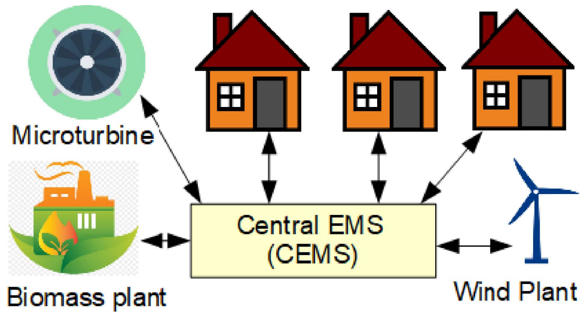
For the sake of simplifying the discussions, solar home system alternative is taken as the study case. The IEC 61850 information models for these components based on the data exchanged is developed next. In a similar fashion, community microgrid solutions can be modeled by using relevant models for SMs, controllers, loads, storage systems, as well as different generators.

A. PV System

The PV system will communicate three types of data: 1) weather forecast and solar radiation data to the server;



(a)



(b)

Fig. 3. *Components of first-access electricity solutions. (a) Solar home system solution. (b) Microgrid solution.*

2) meter data to the HEMS; and 3) monitoring and control data to the HEMS. The IEC 61850 information model of the PV system should contain the appropriate LNs and DOs to communicate the above-mentioned two data sets. The weather forecast and solar radiation data set consists of different weather parameters measured, such as temperature, cloud cover, pressure, humidity, direct insolation, and diffuse insolation. These measured parameters are standardized with different DOs of LN MMET, such as “EnvTmp,” “CloudCvr,” “EnvPres,” “EnvHum,” “DctInsol,” and “DffInsol.” The meter data data set consists of metering values, such as PV power, and this parameter is standardized with DO “TotW” of MMXU LN. The monitoring and control data set consists of three parameters, power output control mode, tracking controller type, and tracking technology that are standardized by DOs “ArrModCtr” of DPVC LN and “TrkTyp” and “TrkTech” of DTRC LNs, respectively. Through the power output control mode parameter, different modes of the operation PV system, such as maximum power point tracking (MPPT), power limiter controller, dc current limit, and array voltage control, may be set.

The PV system control IED consists of primarily the above-discussed, four LNs MMET, MMXU, DPVC, and DTRC. Furthermore, the IED contains two default LNs LLN0 and LPHD1. The IEC 61850 standardized information model of the PV system control IED containing the above-required LNs developed in the InfoTech ICD editor is shown in Fig. 4.

B. Smart Meter

Smart meters deal with the measurement and pricing of energy related to grid and the first-access electricity systems. Hence, the SM communicates two types of data: 1) metered values and 2) pricing data. In order to facilitate

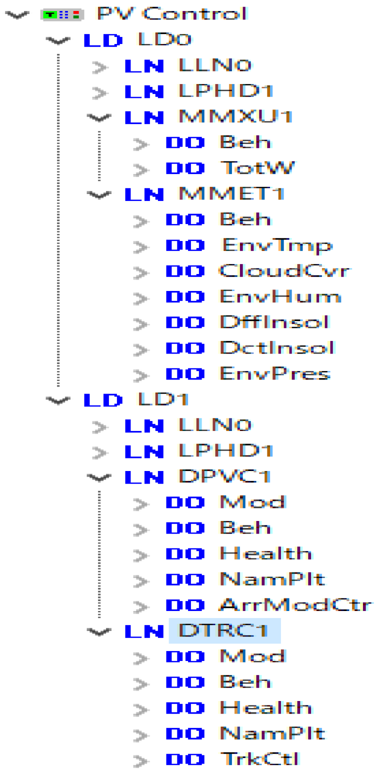


Fig. 4. ***IEC 61850 information model of the PV system.***

Table 2 Description of LGRP LN [44]

LGRP Class			
Attribute Name	*Attribute Type*	*Explanation*	*M/O*
LNName		Shall be inherited from Logical-Node Class (See IEC 61850-7-2)	
Data			
Measured Values			
StoredPrice	CUG	Grid Stored Price	M
CurrentPrice	CUG	Grid Current Price	M
Setting			
GRTime	ORG	Provides Sampling Time for Grid	O
WinTms	ENG	Time Window (in seconds) within which current pricing signal must be applied.	O
CrntTms	ENG	Timeout period for current pricing signal	O

Table 3 Description of LSHP LN [44]

LSHP Class			
Attribute Name	*Attribute Type*	*Explanation*	*M/O*
LNName		Shall be inherited from Logical-Node Class (See IEC 61850-7-2)	
Data			
Measured Values			
StoredPrice	CUG	Solar Home System Stored Price	M
CurrentPrice	CUG	Solar Home System Current Price	M
Setting			
WinTms	ENG	Time Window (in seconds) within which current pricing signal must be applied.	O
CrntTms	ENG	Timeout period for current pricing signal	O

their smooth and interoperable operation, the IEC 61850-based information models of SM need to be developed. The IEC 61850-based information models for SM developed in [47] have been adopted in this article. The detailed communication modeling of SM using the IEC 61850 standard is presented, as shown in Fig. 5.

The SM model contains several LNs corresponding to different functions. The power flow control section is responsible for tracking dynamic power flow using controller interface (ITCI) connected to the first-access electricity system, e.g., SHS. The SHS can be switched between the grid connected to stand-alone mode using switch controller (CSWI), physical switch (XSWI), and tripping

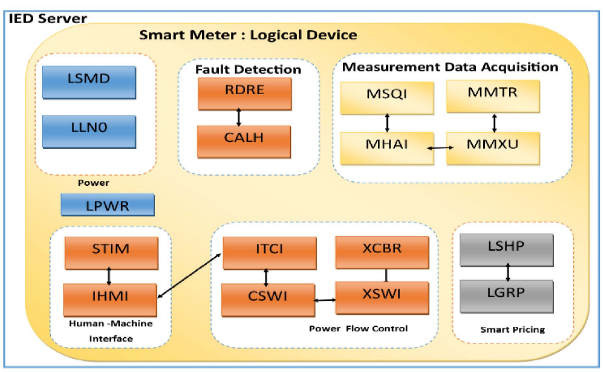


Fig. 5. ***SM modeling with IEC 61850 [44].***

circuit breaker (XCBR). Other specific LNs include MSQI for sequence and inter-harmonics measurement and MHAI for harmonics and inter-harmonics measurement. The protection and fault detection are done with the help of RDER LN, used for disturbance recording and processing.

The measurement or metered data communicated by the SM contains parameters, such as voltage, current, frequency, power, and energy, which are standardized through the DOs “PhV,” “A,” “Hz,” “TotVA,” and “TotVAh” of MMXU and MMTR LNs. To realize the smart pricing functionality in the SM model, LNs’ LGRP and LSHP, developed in [47], are utilized. The description of LGRP and LSHP, i.e., the DOs and its functionalities, is given in Tables 2 and 3, respectively. The LGRP and LSHP LNs contain the DOs “StoredPrice” and “CurrentPrice” for the stored and current prices of utility grid and SHSs, respectively. The time period within which the current pricing signal must be applied is denoted by DO “WinTms,” while the DO “CrntTms” denotes the timeout period of the current pricing signal.

C. Battery System

The battery system communicates the data related to its settings and the measured values to the HEMS. The battery system is modeled with the LN ZBAT

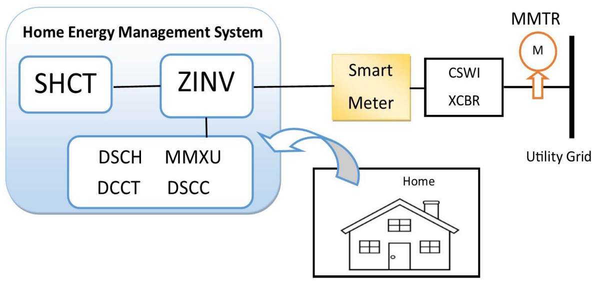


Fig. 6. ***HEMS modeling with IEC 61850.***

containing the appropriate DOs for the data sets communicated by a battery system to HEMS. The battery settings' information, such as the type of battery, Ampere-hour rating of the battery, and maximum battery discharge current, is standardized by the "BatTyp," "AhrRtg," and "MaxBatA" DOs of ZBAT node, respectively. Furthermore, the measured values of the battery system, such as battery voltage, battery drain current, internal battery voltage, and current, are standardized through the DOs "Vol," "Amp," "InBatV," and "InBatA" of LN ZBAT, respectively.

D. Controllable Loads

The controllable loads exchange the data, related to its control and metered values, with the HEMS. The IEC 61850 information model of controllable loads developed in [35] is considered here. Table 4 gives the description of different DOs of the controllable load LN. The controllable load communicates its metered values of active and reactive power being consumed through the standardized DOs "WRtg" and "VArRtg," respectively. Furthermore, the control parameters are related to the interruptible loads, and direct controllable loads are standardized through the DOs "IlcPos," "IlcOpOpn," "IlcOpCls," and "DCLMode."

E. Home Energy Management System

The HEMS system consists of an inverter/rectifier to which the PV system, battery, load, and grid are connected. The HEMS system communicates different data sets with: 1) aggregator (grid); 2) PV system; 3) battery; and 4) loads. The standardized data models (i.e., IEC 61850 DOs and LNs) for the different information exchanges between HEMS with PV system, battery, and controllable loads are already discussed earlier. The data exchanges between the HEMS and the aggregator (i.e., grid) is discussed next.

The interconnecting inverter/rectifier is modeled by ZINV/ZRCT LNs. Furthermore, the HEMS is modeled with SHCT, DSCH, DCCT, DSCC, and MMXU LNs, as shown in Fig. 6. These LNs contain different standardized DOs for all the data information exchanges between the HEMS and the grid.

Table 4 Controllable Load Logical Node (CNLO)

GAPC class			
Attributes	**Type**	**Description**	**M/O/C**
LNName		Shall be inherited from Logical-Node class (IEC 61850-7-2)	
Data			
		LN shall inherit all Mandatory Data from Common LN Class	
Metered Value			
WRtg	MV	Load active power rating	M
VArRtg	MV	Load reactive power rating	M
Controls			
IlcPos	DPC	Interruptible load Yes/No Yes = True, No = False	M
IlcOpOpn	ACT	Operation "Open Switch"	M
IlcOpCls	ACT	Operation "Close Switch"	M
DCLMode	ING	Demand Response Mode Value – Explanation 0 – Load OFF 1 – Load not to exceed 25 % KW capacity 2 – Load between 26-50 % KW capacity 3 – Load between 51-75 % KW capacity	M
V2GEnable	DPC	Switch on/off V2G participation, ON= True, OFF= False	M
V2Gdischarge	DPC	Switch on/off V2G discharge, ON= True, OFF= False	M
V2GChrgMode	ING	Charging Modes Value – Explanation 0 – EV charging at a constant rate 1 – EV discharging at constant rate during peak load 2 – EV Fast charging at light loads 3 – EV status overcharged, discharge at constant rate	M

Initially, the HEMS system based on the forecast and prediction of power generated and load registers its capabilities with the aggregator. In turn, the aggregator provides service schedules for HEMS. These message exchanges between the HEMS and the aggregator are standardized through different IEC 61850 LNs. Through the DCCT LN, the HEMS registers its technical capabilities to the aggregator. The DSCH receives the energy service schedules for HEMS from the aggregator. DSCC LN is used to control or set the energy or ancillary service schedule in the HEMS.

The SHCT LN includes all the necessary parameters to control the connection of HEMS with the grid. The HEMS to grid or grid to HEMS connection time is monitored by DOs "SH2GStart," "SH2GEnd," "G2SHStart," and "G2SHEnd" of SHCT. "SHReady" DO denotes the time interval when HEMS is ready to deliver power into the grid. Similarly, "GridReady" is time duration when the grid is ready for an injection of power from remote distributed resources. "IAlim" and "IVlim" are the parameters for input current and voltage limits, respectively, whereas "OAlim" and "OVlim" are for output current and voltage limits for SH2G operation, respectively. "ConnCount" tracks the number of times grid connected for recording the history of stand-alone or grid-connected operations. "SH2GStatus"

Table 5 Description of SHCT Logical Node [47]

SHCT Class			
Data Name	**CDC**	**Explanation**	**M/O/C**
LNName		Shall be inherited from logical-node class (see IEC 61850-7-2)	
Settings			
SH2GStart	ASG	SH2G-Allowed Connection Start Time	O
SH2GEnd	ASG	SH2G-Allowed Connection End Time	O
G2SHStart	ASG	G2SH-Allowed Connection Start Time	O
G2SHEnd	ASG	G2SH-Allowed Connection End Time	O
SHReady	ASG	Time when HEMS storage and generations are ready to deliver power	O
GridReady	ASG	Time when Grid is ready to receive power from HEMS	O
IAlim	ASG	Input Current Limit	O
OAlim	ASG	Output Current Limit	O
IVlim	ASG	Input voltage limit	O
OVlim	ASG	Output voltage limit	O
SH2GMode	ING	Types of connection modes 1 = As Energy Resource 2 = Demand Response 3 = Ancillary Service	M
Status Information			
ConnCount	INS	Count of grid connection	M
SH2GStatus	SPS	True: SH2G scheme is ON False: SH2G scheme is OFF	M
G2SHStatus	SPS	True: G2SH scheme is ON False: G2SH scheme is OFF	M
EconStatus	SPS	True: Economic Connection is selected False: Immediate connection is selected	M
ConnectSign	SPS	True: Grid Connection Signal is ON False: Grid Connection Signal is OFF	O
StorFullSign	SPS	True: Storage devices full Signal is ON False: Storage devices full Signal is OFF	O
Controls			
SH2GEnable	DPC	Grid Connected or Islanded Operation GridConnected=True, Island=False	M
SH2GSwitch	DPC	Switch SH2G or G2SH connection SH2G=True, G2SH=False	M
EconConnect	DPC	Switch economic and immediate connection, Economic=True, Immediate=False	M
Measured Values			
DelPower	MV	Power delivered to grid by SH2G scheme	O
RecPower	MV	The amount of power received by HEMS	O
SHPrice	MV	The current HEMS price for energy delivery	O
GridPrice	MV	The current grid price for energy supply	O

is set to "True" if power is delivered from HEMS to the grid and "G2SHStatus" is set to "True" otherwise.

"EconStatus" presents whether HEMS is connected to grid for economic power transfer during non-peak and peak times. *"SH2GEnable"* is set to "True" if HEMS is connected to the grid and "False" if it is operating in islanded mode, while "SH2GSwitch" changes its operation from power sourcing ("True") to power sinking ("False"). The switching of different operations can be done by HEMS user or, in case of demand-side management, by the utility grid using the communication configuration. Table 5 gives the description of the different DOs of the SHCT LN HEMS. The measured values section has items of delivered ("DelPower") and received power ("RecPower") as well as pricing for energy generated by SHS ("SHPrice") and energy purchased from the grid ("GridPrice"). These measured values play an important role in power flow control and smart pricing for the realization of the smart grid at the household level.

VI. CONCLUSION

The energy crisis in the developing world and its potential for profit create real business opportunities for first-access electrification projects. Despite this fact, investors are still hesitant to get involved due to the many uncertainties observed; the actual demand for electricity, growth of demand in time, people's ability to pay, and public opinion on different models of electrification are all subjected to significant inaccuracies or even unknown altogether. Normally, such risks are mitigated or reduced for such projects by analyzing the data pertaining to past projects or indicators that may give meaningful results. The biggest challenge of first-access systems is being the very first attempt on electrification with no past data. Furthermore, each project is tailor-made for a specific environment and the lessons learned cannot be reflected on other projects. Most companies do not collect data, but those who do, do it in a non-standard way. This limits the usability of such data by others.

This article discusses the benefits of having a standardized approach to data collection in these systems. This will help each project add to the general knowledge and increase the profitability of future projects by reducing risks and unknowns. The contributions made are threefold. First, the importance of data collection and the value associated were analyzed. Data of prime interest are to cover geographical aspects and communities as well as characteristics of first-access microgrids and the planning and operation involved. Second, data standards were laid out at the system level for microgrids that lend themselves to fostering swarm electrification. In this context, the standards were developed according to the criteria of integrity, security, accuracy, scalability, and efficiency as guiding principles. Meta data, such as location, date, and measurement accuracy, are considered together with energy data counterparts covering information pertaining to generation, load, storage, and so on.

Third, following up upon the system level, a full set of subsystem data based on IEC 61850 was showcased where solar home systems, SMs, PV panels, and storage devices exchange the standardized data. This will ensure plug-and-play operation as devices from different manufacturers can work seamlessly. Standardizing the messages and DOs in consistence with an international smart grid standard that is poised to be used in all future power systems makes this solution more universal. In this fashion, these data systems will not only work as isolated first-access systems but also as integrated networks, if in the future, they are connected to the larger grid. As such, the proposed data standardization for smart infrastructures in first-access electricity systems offers a strong backbone for stimulating growth in this important area. This will ensure plug-and-play operation as devices from different manufacturers can work seamlessly. ■

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