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Novel procedure to formulate load profiles for off-grid rural areas

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ABSTRACT

In this paper, we describe the development, implementation and application of a novel mathematical procedure devoted to formulating the daily load profiles of off-grid consumers in rural areas. The procedure aims at providing such profiles as input data for the design process of off-grid systems for rural electrification. Indeed, daily load profiles represent an essential input for off-grid systems capacity planning methods based on steady-state energy simulation and lifetime techno-economic analyses, and for the analysis of the logics to control the energy fluxes among the different system components. Nevertheless, no particular attention has been devoted so far in the scientific literature as regards specific approaches for daily load profiles estimates for rural consumers. In order to contribute to covering this gap, we developed a new mathematical procedure taking into consideration the specific features of rural areas. The procedure is based on a set of data that can be surveyed and/or assumed in rural areas, and it relies on a stochastic bottom-up approach with correlations between the different load profile parameters (i.e. load factor, coincidence factor and number of consumers) in order to build up the coincidence behavior of the electrical appliances. We have implemented the procedure in a software tool (*LoadProGen*) which can eventually support the off-grid systems design process for rural electrification. Finally, we have applied the procedure to a case study in order to clarify the proposed approach.

Design process of off-grid systems for rural electrification and users' electric consumptions

At the world level, about 1.3 billion people live without access to electricity and nearly 82% of these people live in rural areas of developing countries. This number is not expected to significantly change in the next decades. Indeed, according to the WEO 2014, 0.5 billion people are expected to remain without access to electricity in the New Policy Scenario (IEA, 2014). Moreover, by comparing this scenario with the Universal Access Scenario proposed by the IEA in 2012 (IEA, 2012), it clearly emerges that in order to provide electricity to these people, it is required to consider other options besides the traditional centralized electrification approach. In particular, off-grid systems (i.e. stand-alone and micro-grid systems), mainly based on renewable sources of energy and integrating storage, are often the only feasible solution for the supply of electricity in rural areas. The design process of such systems requires special attention since it deals with unpredictable energy sources, unknown or uncertain electric consumptions and it is a joint matter of cost-saving (affordability), appropriate sizing (reliability) and long-term duration (sustainability). Moreover, the scenario for rural areas of developing countries is complicated by the well-known lack of information about both users' electric consumptions and energy sources' availability. Indeed, in most rural electrification actions, precedent experiences are not available to base the system design on.

Users' electric consumption is a key element in the design process of off-grid systems especially when dealing with unpredictable renewable sources, when integrating multiple sources and when including energy storage. In fact, such information is necessary in the different phases of the design process; e.g. to appropriately perform the sizing of power sources and storage capacities, to analyze and optimize the logics to control the energy fluxes among the different components and to study the real-time power control of the system (i.e. voltage and current regulation).

In the scientific literature, depending on the design phase undertaken and the method employed, information about users' electric consumptions has different degrees of detail:

- Intuitive sizing methods, based on simple algebraic relationships between power requirements and energy sources availability, typically rely on average daily electric consumptions of the targeted group of users (Elhadidy and Shaahid, 2000; Ahmad, 2002; Bhuiyan and Ali Asgar, 2003; Mandelli et al., 2014).
- Capacity planning methods, based on steady-state energy simulation, heuristic or analytical optimization and analyses of the logics to control the energy fluxes among the different system components, typically rely on *daily load profiles* (Barley and Winn, 1996; Shen, 2009; Belfkira et al., 2011; Bekele and Tadesse, 2012). In these cases, load profiles are a numerical series, the values of which define the average constant power load required by the users within a given time-step. Usually, 24 values represent the hourly average powers load which define the daily profile.

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- Real-time power control analyses, based on circuital or block-set models comprising power electronics and system control components, typically rely on short-term load profiles (Ozaki et al., 2010; Chen et al., 2012). In these cases, load profiles are continuous functions which represent the power loads required by the users for a few seconds/min.

It is worthwhile to highlight that in all these methods, besides input data concerning users' electric consumptions, data about the availability of unpredictable renewable sources (i.e. mainly solar and wind) are also required. Obviously, when they are not available, they have to be estimated, and this is typically what occurs in rural areas of developing countries. Nevertheless, for renewable sources, data can be retrieved from weather stations usually located in the main nearby cities, several databases are available (see for example GeoModel Solar; IRENA; NASA; SANEDI), and a number of models have been developed (see for example Graham and Hollands (1990); Oliva (2008); Huld et al. (2012). As regards users' electric consumptions, it can be noticed that no particular attention has been devoted to introducing proper modeling or methods for their estimate.

In this paper, we address this issue and we describe the development, implementation and application of a novel mathematical procedure to formulate daily load profiles. The procedure is based on microscopic data about users' classes, electrical devices and usage habits, and employs a bottom-up stochastic approach to build up a realistic coincidence behavior. Its application addresses the design process of off-grid systems for rural electrification, and in particular capacity planning methods as well as analysis of energy fluxes control.

In Brief literature overview of user's electric consumptions modeling, we provide a brief overview of the literature dealing with the user's electric consumptions modelings and we highlight the lack of a dedicated area of interest in daily load profiles formulation for rural off-grid systems. In Formalization of literature-based approaches to formulate daily load profiles for rural areas, we formalize two approaches to formulate daily load profiles for rural areas on the basis of the unstructured methods sometimes employed in the literature. In New mathematical procedure proposed, we describe the development of the new procedure by introducing the targeted general features, the required input data and we present its mathematical formulation. In Implementation of the new procedure: the software *LoadProGen*, we introduce the algorithm that implements the procedure in a software tool—*LoadProGen*—which supports the formulation of daily load profiles. Finally, in Application of the new procedure in a case study, we present the application of the new procedure for a college in a small town in Cameroon comparing the profiles formulated via *LoadProGen* with the real ones we metered in-field. The detailed input data for this application are reported in the Appendix. They were collected during in-field missions via local observations, surveys and questionnaires as regards people's habits and electrical appliances.

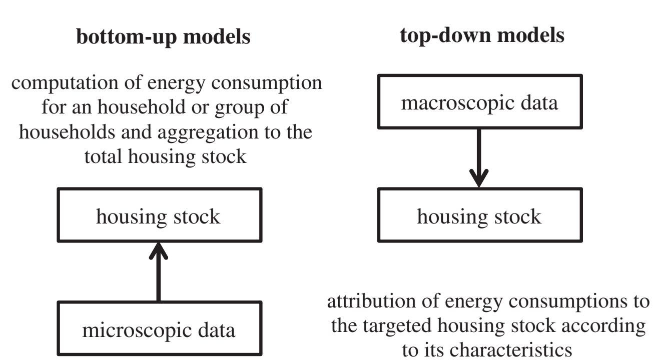

Fig. 1. Bottom-up and top-down model approaches (Swan and Ugursal, 2009).

Table 1
Description of input data required by literature-based approaches.

1.	i	Type of electrical appliances (e.g. light, mobile charger, radio, TV)
2.	j	Specific user class (e.g. household, school, stand shop, clinics)
3.	N_j	Number of users within class j
4.	n_{ij}	Number of appliances i within class j
5.	P_{ij}	Nominal power rate [W] of appliance i within class j
6.	h_{ij}	Overall time each appliance i within class j is on during a day [h]: *functioning time*
7.	$w_{F,ij}$	Period(s) during the day when each appliance i within class j can be on: *functioning windows*

Brief literature overview of user's electric consumptions modeling

The study of user's electric consumptions has been widely addressed within different research themes and with different purposes. These can be grouped into two main areas:

- Power system engineering refers to *load forecasting* as the domain of models able to provide data for setting the best planning and operating of grids. Load forecasting can be divided into three categories: (a) *short term*, which is used to predict loads from 1 h to a week ahead and is required to solve unit commitment and economic load dispatch problems; (b) *medium term*, which is used to predict weekly, monthly and yearly peak loads up to 10 years ahead and is required for efficient grid operational planning; and (c) *long term*, which is used to predict loads up to 50 years ahead and is required for grid expansion planning. Examples are shown in Jia et al. (2001); Al-Hamadi and Soliman (2005); Carpinteiro et al. (2007); Li and Meng (2008); Javed et al. (2012); Liu et al. (2014); and Lee and Hong (2015).
- Energy planning research refers to *energy consumption modeling* as the domain of models able to support energy-related policy decisions. Energy consumption modeling deals with energy consumptions for a country, a region or a sector and they can be grouped into two categories: (a) *top-down*, which is used to determine the effect on consumptions due to ongoing long-term changes in order to assess future supply requirements, and is based on econometric or technological models; (b) *bottom-up*, which is used to model consumptions of each end-use and hence to identify areas for efficiency improvements at user level, and is based on statistical or engineering models (Fig. 1). Examples are shown in Howells et al. (2005); Swan and Ugursal (2009); Song et al. (2011); Zhang and Zhong (2011); Lü et al. (2015); and Xu et al. (2015).

Despite the large number of scientific papers that have addressed these themes, only a few of them specifically focus on the estimate of *daily load profiles* for off-grid systems. Moreover, most of them deal with the particular case of domestic electric consumptions in developed countries and they are mainly devoted to support decisions as regards distributed generation integration in power systems, analysis of

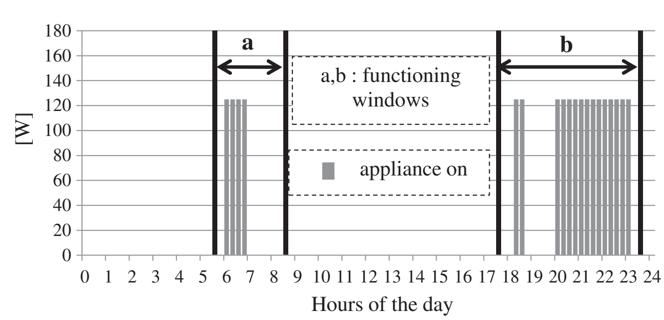

Fig. 2. Graphical representation of functioning windows for a single appliance.