MASTER4all: A decision support model for roadmaps towards sustainable energy universal access for policymakers and utilities

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Abstract

To build strategies for universal access to modern energy services, countries and practitioners require decision support tools that estimate the impact of their choices. MASTER4all provides with useful insights about the trade-offs between different technological, financial, environmental and energy policy alternatives specifically focused on the reduction of energy poverty and the transition from traditional to modern energy supply. The proposed model carefully analyses the national energy system starting with the consideration of multiple user profiles and progressing upstream through supply technologies, transportation and generation, up to the energy sources available. By taking into account detailed policy and technological options, the model enables a transparent and flexible direct policy effect modeling for Universal Access.

Keywords: modern energy universal access; energy poverty, electrification technologies, modern fuels, improved cook stoves, static optimization.

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Introduction

Building a successful strategy towards Universal Access "*to energy services that are clean, reliable and affordable for cooking, heating, lighting, health, communications and productive uses"* (SG AGECC, 2010) requires a careful assessment of the diverse present and future needs of energy services for development from the perspective of the beneficiaries (Brazilian & Pielke, 2013; Schillebeeckx, Parikh, Bansal, & George, 2012). It also needs to bring together suitable innovative technologies, business initiative, frontier financing and regulatory environment according to the country strengths, to make use of the limited resources in an efficient manner (Brazilian, Nussbaumer, Haites, et al., 2010; IFC World Bank, 2012; Khennas, 2012; World Bank, 2010).

To do so, countries need to establish an appropriate framework for the energy transition, involving the final users and establishing the right incentives and regulatory measures to guarantee the long-term sustainability of the supply models. The diversity of user profiles, energy sources, geographic and socio-economic constraints requires the consideration of multiple technological solutions for electrification and modern heat, as well as different business models suitable for each of these circumstances. Regulators and energy authorities need to consider a variety of scenarios and pathways to address universal access, taking into consideration their interactions with other energy, economic, environmental or social policies that need and adequate energy access level, competing for usually scarce government resources. Utilities in charge of electrification of large regions may also find this model useful for the assessment of their investment strategies.

Research Objectives

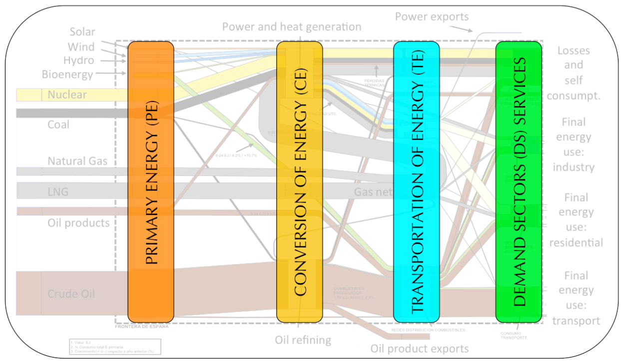
The first research question is how a computer model can support the analysis of trade-offs between universal access and other energy policies at an aggregated country or regional level. IIT has developed a model (MASTER.SO) for analysis of policy strategies in the context of developed economies. The second research question is how to adapt this model to the needs of a developing country.

Objectives:

- Comprehensive consideration of the national energy system zooming in universal access issues with a detailed representation of user needs, suitable technologies and geographic diversity for basic access and possible evolution up the energy ladder.
- Support the establishment of a national energy roadmap to universal access to modern energy services (electricity and heat) together with the interaction with other energy policy targets, with an emphasis on the Sustainable Energy for All initiative (SE4all) targets for energy efficiency and renewables.
- Friendly and interactive representation of the impact of policy choices, suitable for policy decision making, using Sankey diagrams.

Methods

MASTER4all is a model for the analysis of energy roadmaps for Universal Access, together with the interactions with other sustainable energy targets. It is based on the MASTER.SO model, a bottom-up, static (one year divided in 96 time slices), partial equilibrium and linear programming model for the analysis of sustainability policies. It represents the whole energy system based on the Energy flows depicted in the Sankey diagram from the import or national supply of primary energy (PE), conversion of energy (CE), transport (TE) and Demand Sectors (DS) as shown in Figure 1. MASTER.SO follows these flows upstream beginning with a detailed characterization of the energy services required by each economical sector (e.g. residential, industrial, transport, among others) to calculate the optimal supply within a year, minimizing total private costs of energy plus social cost of CO2 emissions. Other political objectives can also be considered as minimizing emissions, fossil fuels, energy use, energy dependency or maximize energy efficiency. For a detailed description of the model and its incardination in the State of the Art, please see (López-Peña, Linares, & Pérez-Arriaga, 2013).



Sankey diagram of the Spanish energy sector in 2011.

Figure 1: Sankey representation and MASTER abstraction model based on (López-Peña, Danesin, et al., 2013)

MASTER4all design derives also of the ongoing joint research by IIT and the Massachusetts Institute of Technology (MIT) sponsored by ENEL Foundation on low-cost energy appropriate technologies, business models and enabling environment for Universal Access and on the previous knowledge of these organizations in the field of energy access technologies, regulation and business models, developed through research and innovation projects with expert practitioners.

Demand characterization

As in MASTER.SO, every demand sector (DS) of the whole energy system is taken into consideration (from industry to transport, losses and non energy uses), but MASTER4all focuses on the customers targeted by universal access in depth, starting with the identification of key energy services (ES) within each sector in the Base of the Pyramid (i.e. the poorest slice of the population) tailored as needed according to the particular characteristics of each country or region):

1. Residential ES: lighting, charging phone, radio, TV, fan, heating, cooking, fridge, washing machine or others
2. Productive ES: specific agricultural, industrial and commercial appliances as pumping, electric saws, sewing machines, or others; depending on the traditional and modern productive sectors.
3. Community DS: street lighting, health, education, sanitation, telecommunications.

Socioeconomic characteristics of the demand are also considered, first with the capacity of payment of different customer profiles, as well as other issues that require specific quantification methodologies, as the cost of non-supplied energy, present traditional energy supply (kerosene or firewood) or economic and demand growth.

For each one of the energy access services, a comprehensive analysis concerning user needs is performed (e.g. hours of light, cooking, cooling or heating requirements, productive uses among others), load profile, demand growth, income generation capacity, contribution to social or development targets, cost of non-served energy and quality of service. The model is customizable according to the level of detail in the input information. Usually the amount of information available regarding household energy services and appliances is very limited in developing countries, mostly present at a very basic level in the national census. Furthermore, actual data regarding commercial and productive uses in the base of the pyramid is even scarcer. MASTER can operate either with a very detailed description of the demand services, appliances and load profiles within each day and year, as applied in developed countries, or with aggregated data and estimation of load profiles for the different energy services provided (ES).

For the estimation of this load profiles, and in order to be able to deduce useful conclusions for policy makers, the model uses a classification of user profiles according to the Tiers of Energy Access (0 to 5) defined by SE4all. This allows that policy targets and commitments can be set properly (Brazilian, Nussbaumer, Haites, et al., 2010) and in accordance to the SE4all Global Tracking Framework (ESMAP, World Bank, & IEA, 2013). SE4all tiers already comprise energy services for the 6 different access levels, therefore providing a meaningful and simplified categorization of the demand that MASTER4all will use not only to describe the initial and final stages of the energy system, but the achievable targets according to different national budget scenarios which allow to evolve up the energy ladder. The model considers energy access tiers not only for residential lighting and heating, but also for productive and community energy services as described by (Practical Action, 2010, 2012, 2013).

Energy system representation

The model can consider the national energy system as a whole (single node approach) or specifically take into account geographical diversity in terms of user profiles, energy services, supply technologies, generation potential and costs (multiple node approach).

The single node approach

For every energy service (e.g. lighting), MASTER4all needs to know the number of users with a present consumption in each Tier, and the maximum and minimum share of each supply technology (ST) choice (e.g. electrification mode):

- Portable Lighting System (PLS).
- Single User System (SUS)
- Micro-grid (MG)
    - Isolated
    - Connected
- Grid extension (GE)

Ascertaining this information for a given country is a difficult task on its own, as analyzed by (Deaton-Steel, 2008). The use of spatial geographic information system energy models can provide detailed data not only about electrification modes, but also about generation potential and costs (Szabó, Bódis, Huld, & Moner-Girona, 2011, 2013). National surveys and electrification plans can provide useful information about grid-connected population while thumbnail rules or more sophisticated expert choice methodologies may also estimate the share of population suitable for each off-grid electrification mode.

For each one of the electrification modes supply technologies (ST) and tier (tr) size, a number of transmission (TE) and generation (CE + PE) options are available with different unit costs (even distribution per time period considering investment plus operation & maintenance and reposition for comparability purposes). For instance, Micro-grids transmission can be AC or DC, and grid extension can use tri-phasic, mono-phasic or single wire earth return (SWER) configurations, with different supply characteristics and also different unit costs. Table 1 shows a non-exhaustive example of look-up table for generation technologies available for each electrification mode, for a given supply tier.

Table 1: Generation alternatives and electrification modes generic look-up table for each SE4all Tier.

gen/mod_{tr}	PS	SU	MG	GE
Grid mix	$cost_{gm,ps}$ [1]	$cost_{gm,su}$ [1]	$cost_{gm,mg}$ [2]	$cost_{gm,ge}$
Solar	$cost_{so,ps}$	$cost_{so,su}$	$cost_{so,mg}$	$cost_{so,ge}$
Wind	$cost_{wi,ps}$	$cost_{wi,su}$	$cost_{wi,mg}$	$cost_{wi,ge}$
Mini-hydro	$cost_{hy,ps}$	$cost_{hy,su}$	$cost_{hy,mg}$	$cost_{hy,ge}$
Biomass	$cost_{bm,ps}$	$cost_{bm,su}$	$cost_{bm,mg}$	$cost_{bm,ge}$
Diesel	$cost_{di,ps}$	$cost_{di,su}$	$cost_{di,mg}$	$cost_{di,ge}$
Hybrid S-D	$cost_{sd,ps}$	$cost_{sd,su}$	$cost_{sd,mg}$	$cost_{sd,ge}$

An equivalent approach is followed for heating and cooking technologies, as well as for traditional energy supply technologies (kerosene, candles, replaceable batteries, three stone firewood and mechanical appliances) to be able to analyze the alternatives for users.

The model does not take into account only the costs of each technology, but also their losses, carbon emissions, indoor pollution or social costs.

The multiple node approach

The delivered cost of power supply in remote areas varies according to the distance to the network, peak electrical load, load factor and cost of decentralized generation (Nouni, Mullick, & Kandpal, 2008). Analogously the cost of modern fuels also depends on the distance to the supply centers. The availability of GIS analysis combined with technological design tools to assess the costs of energy access under different circumstances poses the opportunity to capture in MASTER4all the diversity of energy settings across the whole country. For instance, regarding Micro-grid electrification mode, the GIS can identify villages or clusters of houses suitable for diverse Micro-grid configurations taking into account the specific services, capacity of payment, demand profiles, tiers, number of customers, distance to the grid and between users, generation potential, and even the existence of singular "anchor" customers with high quality demand (such as hospitals, schools or productive facilities).

The multiple node approach requires the classification and quantification of equivalent energy clusters of users (in terms of tier, capacity of payment, ST, TE, CE and PE profile), associated with energy and non-served energy costs, losses, emissions and pollution functions.

Model features

The flexibility of the model, and its capacity to represent user services in detail as well as service technologies and energy sources, makes it very appropriate for analyzing different policy scenarios, objectives and regulatory measures.

Energy access approach

There are two main approaches for energy access (Gaunt, 2003):

The blanket or social approach: It is associated to a political logic frame for equitable energy access, where targets are universal use of electricity for every customer, usually under a rights based approach, environmental improvement, adequate quality and social performance. Blanket approach focuses on minimizing lack of energy access and energy poverty with minimum subsidies.

The selective or business approach is described in three phases: connection, densification and reinforcement. Lower costs and commercial strategies with a focus on productive activities allow small positive financial returns and higher sustainability, but poor households receive access last (or not at all if they cannot afford it). Priority of selective approach is on business model development and market minimization of costs, with or without any subsidy scheme.

Optimization choices

MASTER.SO objective function is targeted to minimizing total private costs plus social cost of CO2 emissions for a particular level of service. In the case of MASTER4all, usually governments will prioritize universal access within a limited budget for incentives or subsidies. Maximization of energy access is attained carefully including in the objective function the cost of non-served energy for each energy access service.

Other energy policy objectives like promotion of energy efficiency and renewable energy can also be considered along universal access by the optimization tool, allowing the study of trade-offs between different policy approaches.

Scenarios and restrictions

The model can be supplied with global restrictions and commitments (e.g. total emissions or indoor pollution maximums, maximum public budget for universal access, funding availability or minimum and maximum operation capacities). It can also be provided with specific targeted incentives and subsidies for certain users, technologies or energy sources. Thus, different scenarios and policy measures can be analyzed, as defined by the user of the model.

[1] Cost of energy of portable batteries charged at grid connected kiosks, used by PSLS and SUS.

[2] Cost of energy for grid connected Micro-grids.

Operation modes

MASTER4all can be set to optimize the investment decisions considering the existence of present capacity (brownfield operation) or without considering any previous capacity (greenfield operation), or to optimize the actual operation of the existing capacity (without investing in any new capacity).

Results

MASTER.Ser4all model provides the "big picture" required to compare different policy choices without renouncing to analyze detailed issues regarding user needs and services, supply technologies and policy incentives and targets. The model is understandable by policymakers and decision makers from incumbent utilities, useful to compare different options already proposed, or even new tailored approaches, and presented in an understandable graphic way.

The model offers also flexibility for providing different energy access metrics, either one-dimensional or set of indicators (e.g. share of electrified houses or modern heat supplied or cost of non supplied energy), composite indexes as Energy for Development Index (EDI) of the International Energy Agency (Brazilian, Nussbaumer, Cabraal, et al., 2010) or the Multidimensional Energy Poverty Index (MEPI) (Nussbaumer, Bazilian, & Modi, 2012) or proxies as indoor pollution.

The model has already been applied to several studies in developed countries, as the comparison of renewables vs. energy efficiency policies in Spain for the reduction of carbon emissions detailed in (López-Peña, Pérez-Arriaga, & Linares, 2012). The novelty of MASTER4all lays in its ability to capture the characteristics of the transition between traditional to modern energy supply and its specificities in terms of user profiles, technological options (both grid connected and decentralized), quality of service, reliability and system constraints for the reduction of energy poverty in developing countries.

Discussion

State of the Art

MASTER.SO model occupies the same space as other mainstream models as MARKAL/TIMES, POLES, WEM, PRIMES, NEMS, EPPA and WITCH, among others. Some models are black boxes, or require many and complex internal parameters and require perfect or ideal behaviors, mainly suitable for expert modeling teams. MASTER.SO provides very fast, simple and transparent insights on the big picture, allowing interaction and an intuitive understanding for policy makers without modeling expertise. It adds to other models in the literature especially in terms of transparency, direct policy effect modeling, synergies/trade-offs analysis and slightly in modeling flexibility; keeping technological detail and sacrificing economic representation and behavior of real energy markets (López-Peña, 2014).

MASTER4all builds over the same methodology, incorporating the user-centric approach to Universal Access policies according to (Schillebeeckx et al., 2012), focusing on the needs, profiles and charecteristics of the population with lack of (or unreliable) supply of modern energy services.

Scope and limits of the model

The main limitations of this model come precisely from the difficulty to capture the details of technological complexity and the diversity of actual energy supply throughout the geography of a developing country, especially in terms of data availability. The model acknowledges these limitations, especially if operating under the multiple node approach. Therefore, for the study cases actually under development in Kenya, Peru and India, we are developing a complementary approach using GIS and system design reference models, required appropriately to establish the boundaries between different electrification and heat supply modes.

A second limitation of the model derives from its static nature, which allows us to assess the effort required for achieving a particular final Universal Access target, but it does not provide information about the intermediate stages of the process. The development of a dynamic version of MASTER4all is a future research line.

Finally, the purpose of this model is not to provide the most precise projections, but valuable insights about the magnitude of the universal access effort and comparison criteria between different scenarios and strategies.

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