A Systems Approach to Regional Energy Modeling with Smart Grid Integrated Distributed Energy Resources

By Frédéric Babonneau, Michael Caramanis and Alain Haurie

INTRODUCTION

It is now well recognized that the drive toward sustainable development can be facilitated by adopting smart energy systems relying on the interface and co-optimization of the cyber and physical layers modeling the Electricity Cyber Physical System (CPS). Regional energy systems will be profoundly transformed by the increasing penetration of intermittent and variable renewable energy (VRE) sources connected at transmission (e.g., wind farms) or at distribution (e.g., rooftop PV panels) networks. At the same time, the advent of grid friendly flexible loads (FLs) and distributed energy resources (DERs) including variable speed drive powered CHP microgenerators [5], heat pumps [9], and electric vehicles [6,12], will provide new options to develop demand response and provide distributed system services. VRE will impose new operational requirements, but, fortunately, FLs and DERs provide new opportunities to optimize power systems through the provision of fast reserves and dual use of accompanying volt/var control devices (PV inverters, EV chargers and the like). Under these circumstances, FLs and DERs can significantly improve operational and investment efficiencies.

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Grid operators (GOs) and agencies entrusted with planning sustainable development at the regional level, for example those in charge of developing territorial climate energy plans in Europe (e.g., in France, Germany or Switzerland), or those promoting the development of smart cities in the Gulf region (e.g., Lusaï in Qatar or Masdar in Abu Dhabi), must cooperate to redesign the local energy system. To succeed in the transition to a non-fossil fuel based renewable energy future, new designs should embrace the generation as well as the consumption sides (see Mathiesen et al. [11]) through the adoption of Smart Energy Systems (SESs). This requires investments in a number of appropriate infrastructures including smart electricity grids, smart thermal grids (district heating and cooling), smart gas grids and other fuel infrastructures. There is, therefore, an urgent need to develop a new planning framework based on a Systems Analysis approach at the regional level capable of capturing the synergies of SESs with smart grid integrated DERs (e.g., OSeMOSys [7]).

ETEM-SG provides such a framework. It has been designed to integrate within a computationally efficient Linear Programming framework explicit constraints on reactive power compensation, secondary reserves, electric vehicle (EV) charging, and variable loss of life of network assets such as transformers. In this respect it complements the model listed above and provides a more precise assessment of the potential offered by SESs in fostering extensive penetration of VREs.

ETEM-SG: A LINEAR PROGRAMMING MODEL FOR REGIONAL ENERGY SYSTEM PLANNING

DERs can be thought of as small, albeit numerous agents acting in a distributed fashion. For example, the owners of EVs may have the option to participate in demand response programs controlling the charging of their vehicles by local computer intelligence that synthesizes EV owner preferences (e.g., desired departure time) and GO information communicated through the smart grid cyber layer. Typically, GO information will be indicative of the marginal cost of electricity at different times and grid locations. A local on-board computer will be programmed to optimize the charging of the battery in response to GO communicated dynamic prices. Load aggregators may facilitate this process. Since each EV is a very small consumer, it can be thought of as a price taker whose charging decisions have no influence on the price. In fact, it can be shown that, under reasonable conditions, the optimal decisions taken by many small optimizing agents reacting to marginal cost based dynamic prices are consistent with the decision the GO would take to minimize system cost, if it were able to directly control the charging of classes of EVs (See [1]). Indeed, the introduction of smart controllers may facilitate the implementation of socially optimal marginal cost pricing of electricity.

Linear programs have been used with success to discover marginal cost based prices of electricity that prevail at different times of the day and different seasons in the year. Linear programs have also been used with considerable success to develop a systems analysis of the long-term evolution of the whole energy sector in a country or a region (see in particular TIMES [8] [3] or OSeMOSYS [7]). ETEM-SG is a linear programming model, designed for the prospective analysis of regional energy systems (see [2]) that is very similar to TIMES. The energy system is driven by price-quantity bids for energy (or energy services) by market participants, and by the price of energy imports. The model takes into account all possible energy and technology options, at the levels of extraction, generation, transformation and usage of primary and final energy forms. Each technology is characterized by a date of availability (if it is a new technology), a life duration, an installed capacity, which can be increased through investment, and an operating strategy. Three categories of costs are considered, investment cost linked to capacity increase, maintenance cost linked to installed capacity, and operation cost linked to the operating process. These costs enter in the definition of a total discounted system cost, which is used as a performance criterion in the associated linear program. The model can account for global emissions of local pollutants (NOx, VOCs) and of GHG (CO_2, CH4). ETEM-SG is used to analyze the path of energy transition at a local/regional level. A particular feature of ETEM-SG is its ability to take into account the constraints and optional strategies and preferences of smart power systems at the distribution level.

MODELING OF SALIENT DISTRIBUTION NETWORK COSTS, BENEFITS AND DYNAMICS

In ETEM-SG the electricity production sector is modeled with special care devoted to distributed energy resources (DER) - EVs/PHEVs, heat pumps, solar panels and the like - , the management of demand response and system ancillary services, such as secondary reserves and reactive power compensation. ETEM-SG uses a simplified representation of the transmission system. Centralized conventional generators and wind farms are connected to a high capacity transmission network that is approximated by a single congestion free "infinite" bus. The production of wind generators incurs no variable cost. The distribution network is modeled by n radial distribution feeders connected to the "infinite" bus. Each feeder bus hosts: (i) demands corresponding to conventional inflexible loads (e.g., lighting), which consume "reactive power" depending on a constant power factor, (ii) flexible loads (typically EV battery charging, variable speed drive heat pumps for space conditioning), and (iii) PV generation. EV battery chargers and PV inverters can provide reactive power compensation, as needed, when they have excess capacity, for example when the sun does not shine enough to fully utilize the DC to AC inverter of the PV facility or when the EV battery is not charging at the charger's capacity. During a given time-slice, flexible loads create value (or utility to their owners) by providing a service such as space conditioning that maintains inside temperature within a comfort temperature zone, increasing the state of charge of the EV battery and the like. Although in principle other types of reserves can be also modeled, we focus on secondary reserves made necessary by renewable generation and uncertainty in conventional loads and generation. The reserves required by the system operator can be provided by conventional centralized generators but also by the flexible loads, in particular by the PHEV/EVs. When the apparent power flowing through a feeder's transformer rises close to or exceeds its rated capacity, the transformer's life degrades rapidly contributing to distribution network's variable costs. High apparent power flow is also associated with high distribution line losses. Reactive power compensation decreases the apparent power flow providing significant cost reduction through lower energy losses and transformer life degradation. In addition, requiring less reactive power at the infinite bus, reduces further the grid opportunity cost associated with the provision of reactive power compensation at the substation. The production of energy by conventional generators is associated with a marginal cost corresponding to the short run marginal costs of the marginal generator. The linear program determined flexible load and DER capacity allocation among real power, reactive power and reserves that minimizes grid costs and participant costs minus benefits, subject to load flow, voltage, energy balance and reserve requirements constraints.

ILLUSTRATION WITH ETEM-SG

An implementation of ETEM-SG has been realized, taking a region of Switzerland as a case study. The region, called "Arc Lémanique" regroups the cantons of Geneva and Vaud. Three aggregate feeders are modeled corresponding to the grids of the three main operators, SIG in Geneva, SIL in Lausanne and Romande-énergie in the Vaud canton. We compare two scenarios to illustrate how smart energy systems can foster penetration of VREs, by allowing FLs and DERs to provide secondary reserve, reactive power compensation and demand response at different levels. The first scenario assumes that EV batteries and heat pumps can be used to satisfy reserve requirements while in the second scenario this option is not available. Both scenarios assume the same demand for energy services, like transport and space heating, the same prices for imported energy, including electricity and the same stringent emissions reduction objective that corresponds to the official "New Energy Policy" defined by the Swiss Federal Energy Board [15]. In these simulations we assume a reserve factor of 0.5 to cover wind generation, a system reserve of 0.2 to cover load and a power factor of 0.93 associated with reactive power consumption by conventional loads of 0.35 KVar for each 0.93KW that they consume.

The results of simulations, performed for a 2025-2050 planning horizon, show that smart grid integration of FLs and DERs would facilitate VREs penetration.

Figure 1 shows higher VREs penetration in Scenario 1, i.e. 63% of total electricity generation in 2050 from wind turbines (E08) and solar panels (E07), compared to scenario 2 with only 41%. This increase is essentially due to a stronger penetration of wind units.

This is permitted by the exploitation of flexible loads, providing secondary reserve as shown in Figure 2. Note that the 41% observed when smart systems are not fully used is close to the current practice, which recommends a maximum 30-40% share for VREs.

The other production technologies are gas combined-cycle power plants (E0F), gas turbines (E0E) and hydro power plants (E01 and E02). We notice that imports, assumed to be carbon free in this exercise, are needed in scenario 2 to satisfy the emissions reduction constraint. These imports come from Europe and other regions of Switzerland as we don't distinguish them in the model.

We notice in Figure 3 that in both scenarios EVs penetration (TES) is much needed to reach the GHG emissions reduction objectives. The share is even higher in scenario 2 to compensate VREs reduction. Other cars are hybrid (THY) and diesel (TE1) vehicles. In the residential sector, the situation for heating is very similar in both scenarios with investment in heat pumps technologies (i.e., around 20% of the heating sector). Finally, we observe that when smart systems are considered (scenario 1), flexible electricity demand from heat pumps and electric vehicles reaches around 21% of total electricity consumption in 2050.

CONCLUSION

When modeling local/regional energy systems, in a smart grid or, more generally, smart city environment, it becomes very important to represent the constraints, costs and capabilities that are present in distribution networks. With ETEM-SG, local/regional energy and environment planners have the possibility to propose coherent scenarios for the massive penetration of VRE power generation accompanied by the development of smart grid operations, permitting demand-response, distributed reserves as well as distributed reactive power compensation, and the like. The model is currently being tested on case studies of the Arc Lémanique region, in Switzerland, the region of Doha in Qatar, and the non-interconnected regions of the French islands (la Réunion, Corsica, etc.). The first implementations have shown the model's ability to exploit the new potential for efficiency improvement provided by smart grid integration of distributed energy resources. In particular, the scenarios demonstrate the contribution of smart grid integrated flexible loads and distributed energy resources to the efficient adoption of solar and wind generation.

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