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Simulating the diffusion of smart energy behaviour among consumers: an application to Italy

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Abstract

The research aims at verifying the potential of smart grids for promoting sustainable innovation in the power system, with a specific focus on the medium term effects of household adoption of behaviours that may reduce greenhouse gas emissions related to energy use. To do so, a system dynamics model is developed to evaluate the potential dynamics of consumer adoption of a set of "smart energy behaviour" that include: (i) shift of consumption to less expensive (less polluting - congesting) hours, (ii) reduction of consumption while maintaining similar comfort levels, (iii) behaviour and home automation, (iv) enrolment in demand response programs, (v) energy efficiency improvements, (vi) electricity autonomous generation: more in general, we will refer to these activities as 'smart energy behaviours'. These behavioural changes are triggered by the installation of advanced-metering systems and a tariff policy that prices electricity according to time-of-use and promoted by several information diffusion channels (word of mouth, information campaigns, advertising, media coverage, demand-side-management) and catalysts. The model proposed is general but results are presented for a case-study on Italy, where the largest roll-out of smart meters has taken place. A set of 2500 simulations with stochastic parameters is performed to take into account uncertainty in their estimation. Results indicate that consumer engagement may induce behavioural changes that generate shift and reduction in household electricity consumption, which in term induce several benefits in terms of cost reduction, avoidance of greenhouse gas emissions and capacity expansion.

Keywords: Smart Grids, System Dynamics, Consumer behaviour, Energy, Climate change.

1 Introduction

The basic qualitative structure of the power system, up until very recently, had sot changed since the last century. Only in the last decade research has started to focus on ways of innovating the system making it more reliable and responsive. More in detail, I&CT features are starting to be introduced in the power network, so that it can be managed more efficiently and in a timely matter. Much effort is being put in 'making the grid smarter'. This is based on the possibility of transmitting not only energy but also information. This is particularly important as energy demand has been, and will continue to be, increasing per se and related to a gradual electrification of the power supply. Moreover, the power mix needs to drastically change to respond to the need to reduce energy related greenhouse gas (GHG) emissions in relation to climate change mitigation issues. The greater role that intermittent renewable sources are having and will have require a change in the way the system is managed, requiring a faster and capillary control.

Smart grid innovation potentially allows a change in the architecture of the power system enabling also a greater interaction and empowerment of end-users, that have always had a very passive role in the system and have been keep very distant from any decision. Indeed, power generation planning and investments have always been centralised. If enhanced to their full potential smart grids are able to make the power system become a social-technical system where new technological developments are enhanced by their interaction with people, and where top-down planning decisions are integrated with bottom-up initiatives. This is in line with the increasing research that calls for a greater involvement of citizens/consumers for tackling global environmental problems like climate change. Such a structural change needs to be accompanied also by a change in the modelling tools used to study the phenomena.

The aim of the research is to verify the potential of smart grids for promoting sustainable innovation in the power system, with a specific focus on the medium term effects of household adoption of behaviours that may reduce greenhouse gas emissions related to energy use. We refer to these behaviours as 'smart energy behaviours' as they are enabled by the deployment of so called smart meters. More in detail, the research aims at analysing and linking all the drivers that promote the uptake of these behaviours by households, highlighting the feedback structures. Moreover, it aims at identifying diffusion dynamics to evaluate the economic and climate change mitigation potential effects of engaging end-users, identifying the impacts of the studied changes of behaviour on power demand, costs and GHG emissions. The emerging dynamics can be fed into integrated energy-climate models that are used to inform energy and climate change policy. Such models tend to study top-down centrally planned decisions and have not up to now given much attention to consumer engagement except for energy efficiency. The work presented here is just a first attempt to propose a way of modelling such a complex phenomenon. A general model that can be applied to different countries is presented together with a first application - based on available data - to the specific case of Italy where the first full roll-out of smart meters for residential consumers has taken place.

2 How smart meters change the setting

Smart grids include many different types of technologies and grid innovations. This work focuses on advanced metering systems (also referred to as smart meters) as they allow the interaction with end users. Such devices allow a bi-directional flow of electricity and a two-way flow of real-time information. This allows both utilities and consumers to have more and more frequent information that can be used, on the one side, to manage the system and the loads in a more efficient and responsive way, and, on the other, consumers to be more empowered. Indeed, they are able to become more aware about the costs of the energy services (lighting, refrigeration, food preparation, washing, entertainment, heating, cooling, etc.) that they use every day and, possibly, allow to optimize choices according to preferences. Indeed, smart meters may directly or indirectly (through other related devices or services) provide informational feedbacks very close to consumption, attaching a price to the service (Darby, 2006).

Moreover, households/consumers may become also producers of electricity and generate power that can be put into the grid. Even if, at the current state, this option does not effect much a county's energy mix, qualitatively it is an organisational game changer allowing consumers to change their role into 'prosumers' and allowing for new actors and/or aggregation possibilities to emerge.

Finally, advanced metering systems allow options also in terms of policies, as they indeed are able to support changes in tariff structures that were previously not applicable. Indeed, time-related tariffs may be introduced. These are particularly interesting from an economic point of view as they can convey price signals to consumers highlighting that electricity consumption is not a ‘homogeneous’ good, and that related costs and impacts depend on the time of use.

3 Data and methods

3.1 Modelling approach

The model analyses the diffusion dynamics of a set of electricity-related behaviours by households enabled by smart-meters. This has not yet been given enough attention by the economic modelling literature, even if in our opinion it represents one of the most interesting changes triggered by smart grids.

The complexity of the decisional processes of the end-user when deciding his energy management strategies, now enriched with new additional options, poses some methodological issues in the selection of the modelling platform to use for the analysis. System Dynamics models are well-suited to study the behaviour of complex systems characterised by feedback structures, non-linear interdependences and temporal lags (Forrester, 1961; Forrester 1991; Sterman, 2000). Their endogenous nature of system dynamics models (Richardson, 2011) is particularly appropriate to study the diffusion of behaviour (Ulli-Beer et al., 2010; Saeed, 2014), whereby the number of behaviour adopters has an impact on the rate at which the behaviour is adopted by others (Bass, 1969) and informational feedback structures are important drivers (Sterman, 2000).

3.2 Model structure

The basic structure of our model builds on the Bass innovation diffusion model (Bass, 1969) and on the Susceptible-Infectious models used in epidemiology to describe the evolution of epidemics (Murray, 2002). In addition to the fact that the model here presented included more and drivers and interaction channels, there are some important differences from the above-mentioned models that need to be highlighted. Indeed, the adoption is voluntary; moreover the costs are not monetary but in terms of personal effort, while the benefits may be economic and environmental ones.

Focusing on the model structure, the stocks of the model are groups of people that are in different states of behaviour referred to as ’smart energy behaviours’. These are organised in three main not mutually exclusive branches related to electricity production, consumption and involvement in demand response programs. More in detail, the variety of consumer behaviour is modelled on the basis of six options that can emerge once smart meters and tariff policies are in place. Indeed, our model comprises: (*i*) shift of consumption to less expensive (less polluting - congesting) hours, (*ii*) reduction of consumption while maintaining similar comfort levels, (*iii*) behaviour and home automation, (*iv*) enrolment in demand response programs, (*v*) energy efficiency improvements, (*vi*) electricity autonomous generation. On the basis of these behavioural options, consumer behaviour is modelled through ten different ’styles of behaviour’ that each consumer may adopt. These are depicted in the squared boxes of Figure 1 and are characterized by different levels of the six previously described activities.

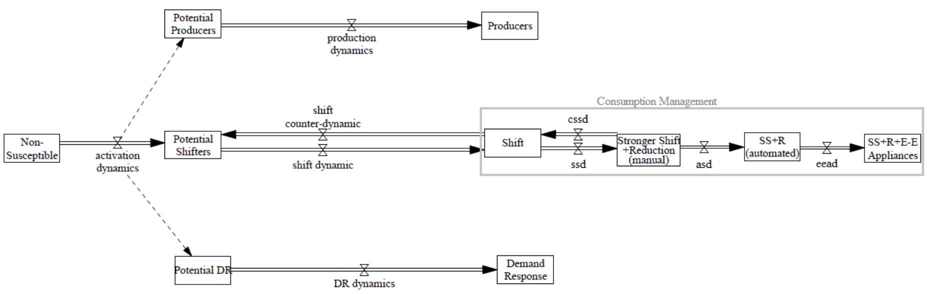

Figure 1: Stock and Flow diagram

The flow of households from one stage to the others is influenced by many factors; the motivational drivers that are modelled are (*i*) economic savings and (*ii*) environmental and societal benefits; while the main informational channels included are: (*i*) information campaigns, (*ii*) demand-side-management policies, (*iii*) word of mouth, (*iv*) media coverage, and (*v*) advertising.
The main structure of the model is quite general and can be applied in different contexts. The first calibration of the model has been applied to Italy. A more detailed description of both the general and specific case-study model can be found in Ricci (2013).

3.3 Data

The possibility to adopt the set of smart energy behaviours analysed in this paper is only very recent and, in some cases, not even available yet. For example in the case of Italy demand response programs for households have not yet been implemented. Therefore there are strong data issues that limit the analysis. However, it is important to try to include the option of engaging with final energy users in energy and climate decisions especially given that investment in energy generation and distribution capacity are very long-lived.
Data availability is quite limited. The current model is based on available data provided by the Italian electric energy authority and by reports on international and national pilot initiatives. Data on changes in consumption following the smart meter roll-out is being collected and, possibly, will be freely available soon. Once more data is available it will be much easier to calibrate the model.

3.4 Model implementation

To respond to the low availability of data and to the uncertainty in the model calibration, the model is run with stochastic parameters. Indeed, 2500 simulations were performed where the values of the parameters are obtained by joint independent random sampling from beta probability distributions centred on the values found in the literature. Moreover, a sensitivity analysis was also run highlighting the most crucial parameters that strongly influence the model outcomes.
Once the adoption dynamics have been identified, these are translated into impacts taking into consideration the dynamics of the median curve. Indeed, each of the ten behavioural stages analysed are associated with a specific level of intensity of the six behaviours. Data was taken from the results of national and international pilot studies that give indications on the extent to which electricity consumers change their behaviours following the installation of smart meters and/or the application of differentiated tariffs (Ehrhardt-Martinez *et al.*, 2010; Olmos *et al.*, 2010; eMeter, 2010).

4 Simulation results

What emerges from the simulations is that even if we run the model taking into account a certain degree of uncertainty in the parameter estimates, the resulting dynamics are not so different. Indeed, given the nature of the research question, the different simulations provide quite robust indications of how it may be interesting to engage with electricity final consumers. Focusing only on the central branch related to consumption management and aggregating the impacts of the people in the different stocks, what emerges is that consumption shift starts from 2010 and grows fast, at nearly one percentage point per year between 2015 and 2030. More in detail, shift in household consumption may reach 13% of aggregated demand by 2020 and 30% by 2030. Electricity consumption reduction presents similar trends (3% by 2020 and 9% by 2030), but starts later in time and reaches lower values with a lower slope, possibly due to the increased effort and/or comfort loss entailed in consumption reduction with respect to consumption shift. The value of shifting consumption is related to the patterns of electricity demand, which are not constant during the day or the year, but are instead characterised by peaks. Electricity generation and transmission systems are sized according to the maximum peak load (plus a margin to account for forecasting errors or emergencies), as demand needs to be satisfied at all times. This means that part of the capacity installed is used only for a very limited amount of hours during the year. Therefore, shifts in consumption that smooth load curves may give the possibility to delay capacity expansion and to better use the available capacity, lowering overall plant and capital cost requirements. In addition to the generation capacity savings, consumption management enables to avoid, or defer in time, also transmission capacity expansions; though these benefits are not accounted for in this analysis.

In relation to the above changes in the consumption patterns, also annual CO_2 emissions related to electricity generation may be cut by 2 Mton (in 2020) and 5 Mton (by 2030) confirming the value of consumer participation.

Furthermore, cost savings can be accrued by the shifting behaviour adoption dynamic that emerges from our model in the order of 0.4 billion €/y by 2020 and 1.2 billion €/y by 2030. Additional economic and environmental benefits are induced by electricity consumption reduction. It is important to underline that the analysis evaluates reductions with very limited change in comfort levels for the household members, indeed we refer to savings of wasteful power like vampire loads and/or automated reduction of consumption. At the household level, annual bill savings related to consumption reduction range between: 19-46 €/household for a 5% reduction, 38-93 €/household for a 10% reduction, and 76-185 €/household for a 20% reduction. As a reference, recall that vampire-loads in the EU are estimated to represent 10% of total residential consumption (ACEEE, 2008).

Consumption reduction has a much stronger economic saving potential for the consumer with respect to the shifting saving potential. Consumption shift away from peak time segments is efficient in allowing economic, environmental and capacity savings for the system, while economic savings for the customer - with the current tariff scheme - are very low, even if they are prospected to grow in the coming years.

Savings due to consumer engagement are high, especially if we consider that they have no (or very little) generating costs, indeed the costs are mostly in terms of effort by the consumer. Here emerges the importance of engaging with the consumer, to make him more empowered and conscious of the multi-level impacts of its consumption decisions.

4 Conclusions

What emerges from the analysis is that there is value in engaging the end consumers to promote sustainable innovation in the power sector. Indeed, quite mild and simple changes in electricity consumption behaviour are able to generate interesting medium term effects that can support climate change mitigation policies and reduce capacity expansion needs for power generation, which entails also environmental and social benefits. Indeed, the smart energy behaviour epidemic seems to be able to spread over time, i.e., the consumer can be successfully involved in the better management of the power system, if the correct signals in terms of price, information and knowledge are put into place.

The speed of the diffusion of the different smart energy behaviours is strongly influenced by the actions of policy makers, electric power providers and other economic agents that might be interested in entering the market following the newly enabled options. The role of utilities is particularly interesting as they are a key player in the full development of the socio-technical system that may be generated by smart-grids. Literature highlights how utilities (in addition to consumers and society at a whole) may gain by the interaction with final consumers especially in remote or delicate areas of the power grid. However current revenue schemes are only related to quantity, thus many utilities are not promoting a more proactive role among their consumers. Thus there is a need for policy interventions that may avoid the contraposition between small and large players and promote synergic interactions that generate environmental, social and cultural benefits.

Future developments will calibrate the model with more data and work on extending the boundaries of the model (e.g., making impacts endogenous). Furthermore, efforts will be made to also improve consumer behaviour modelling and increase the set of behaviours, to include storage services via electric cars.

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