A multi-agent system approach to model the interaction between distributed generation deployment and the grid

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ABSTRACT

This paper introduces a multi-agent dynamical system of the interaction between electricity consumers, the electricity distribution system operator, and the technological (generation, storage) and regulatory (tariff design, incentive schemes) environments. For any type of environment, our dynamical system simulates the evolution of the deployment of distributed electricity generation, as well as the evolution of the cost of distribution. The system relies on the assumption that individual electricity consumers behave statistically as rational agents, who may invest in optimised distributed renewable energy installations, if they are cost-efficient compared to the retail electricity tariff. The deployment of these installations induces a change in the aggregated net consumption and generation of the users of a distribution network. By modelling the cost recovery mechanism of the distribution system operator, the system simulates the evolution of the retail electricity tariff in response to such a change in the aggregated consumption and production.

INTRODUCTION

The integration of distributed electricity generation technologies (DRE), such as solar photovoltaic panels (PV), into the distribution networks (DN) has been made possible by the use of incentive schemes, as these technologies used to be less economically competitive than conventional ones [1]. The inclusion of a sizeable amount of DRE installations, nonetheless, may cause severe strain on the distribution systems, since they are not engineered to absorb large amounts of distributed generation (DG) [2]. The nature of the strain imposed on the system can be multifaceted, and may stem from technical problems such as over-voltages in the low voltage distribution system [3], or regulatory problems including the over-compensation of DRE owners and the potential failure of the cost recovery mechanisms of the distribution system operators (DSO) [4].

In our work, we aim at creating a methodology for testing the impact of any regulatory and technological environments on the deployment of DRE installations and on the distribution component of the retail electricity tariff (simply distribution tariff from now on). The methodology we describe in this paper is based on a multi-agent discrete-time dynamical system formalisation, in which the agents interact with an environment. On the one hand, the agents of such a system are the DRE owners, the non-DRE owners, and a (unique) DSO. On the other hand, the environment (the DN), is composed of a set of rules including the aforementioned incentive schemes, the tariff design of the DN (e.g. volumetric tariffs or capacity tariffs), and the cost of distributed generation and storage technologies.

The purpose of this paper is to describe and test this methodology. In particular, our main contributions are the following:

- We provide a description of our multi-agent discrete-time dynamical system formalisation, used to simulate the evolution of an electricity distribution system by modelling the interactions of individual agents (DRE owners, non-DRE owners, and DSO), with the environment. This is presented in the Methodology section.
- We introduce a test case in which we compare different incentive schemes. In particular we compare two distinct compensation mechanisms (net-metering and net-purchasing) as described in [5]. This is explained in detail in the Test Case section.

METHODOLOGY

In this section we elaborate on the modelling of our multi-agent discrete-time dynamical system. The purpose of such a system is to evaluate, over a given time horizon, and for any environment,

1. the impact of the environment on the rate of adoption of DRE installations; and
2. the impact of the penetration of a significant amount of DRE installations on the distribution tariff.

The result of the first evaluation impacts the second one, which in turn also influences the first evaluation at the subsequent time step, through a feedback mechanism.

In the proposed approach, electricity consumers, interacting with a unique DN, are modelled as rational agents that may invest in optimally sized grid-tied DRE installations if these are cost-efficient compared to the retail electricity tariff. Moreover, the distribution tariff is adapted according to the evolution of DRE generation within the DN. In this framework, three distinct components defining the behaviour of the agents: (i) the *optimisation of DRE units*, (ii) the *investment decision process*, and (iii) the *computation of the distribution tariff*. As a reminder, the agents are the DSO and the users of the DN. There are two distinct groups of users: group A which denotes the users who may deploy a DRE installation, and group B, which comprises the users who cannot invest in a DRE installation due to technical or economic constraints. The latter is therefore left out of the two first components (optimisation and investment decision), since these two, as discussed below, assign the optimal sizing configuration and the investment decision on DRE installations.

Our multi-agent discrete-time dynamical system works as follows. At the initialisation of the system, we assume zero installed DRE capacity for all users. Then, at every time-step, and assuming a tariff design based on volumes of energy traded, the system updates the proportion of consumers who have deployed a DRE installation, as well as the distribution tariff. The detailed work flow of the model is represented by a data flow diagram in Figure 1, and the full description of this multi-agent system, including the code, can be found in [6]. The three components are described in the following.

Optimisation of DRE units

As represented in Figure 1, all potential DRE installations (group A) are optimised following the first component of the multi-agent system. Assuming that the storage dynamics and the investment costs of the DRE can be described by linear mappings, we formalise this optimisation problem as a linear program (LP). The inputs of this LP comprise the consumption and the potential production profiles of each individual agent, as well as several parameters that are user-independent (i.e. the same for all the users). These parameters are the prices of PV and battery, the retail electricity tariff at every time-step, and the efficiency, the depth of discharge and the lifetime of the batteries. The potential DRE installations are optimised so as to minimise their levelized cost of electricity (LCOE). Thus, the resolution of this optimisation problem outputs the optimal sizing configuration (PV and battery capacities) that leads to a minimised LCOE, as well as the LCOE, which is the objective function. We use a standard definition of the LCOE in this model: the average total cost to deploy and operate a DRE installation, divided by the total energy consumed by the user over the project lifetime. The LCOE is formulated according to equation (1):

$$LCOE = \frac{i_0 + \sum_{y=0}^{Y-1} \dfrac{\xi_y}{(1+r)^y}}{\sum_{y=0}^{Y-1} \dfrac{d_y}{(1+r)^y}} \qquad (1)$$

where the capex are represented by i_0, the yearly opex at year y are ξ_y, the yearly demand at year y is defined as d_y, and r represents the discount rate. Finally, the lifetime of the DRE installations (i.e. the optimisation horizon of this LP) is set to Y years. Note that this horizon is not the same as the horizon over which the evolution of the multi-agent discrete-time dynamical system is studied.

Investment decision process

This component is used to decide, for each individual agent in group A, whether to deploy a DRE installation with the optimised sizing configuration indicated by the DRE optimisation. To model such a decision making process, we make use of a price ratio between the optimised LCOE of each agent, and the retail electricity tariff at every time-step of the dynamical system. Such a price ratio, denoted by Γ, will adopt a value in $[0,1]$, since the LCOE of the DRE installations cannot be greater than the retail electricity tariff due to optimality constraints (since the DRE installations are grid-tied, the feasible region of the optimisation problem is upper bounded by the retail electricity tariff). Then, by using a Bernoulli distribution in which the probability p is a linear function of the computed Γ, the investment decision can be controlled by a random variable β drawn from the distribution $B(1,p)$, where $\beta \in \{0,1\}$ by definition of the Bernoulli distribution. According to such a linear function, low values of Γ (i.e. when the LCOE of the optimised DRE unit is of reduced proportions compared to the retail tariff) result in high probability p of drawing a variable $\beta = 1$, which indicates a positive investment decision. Similarly, when Γ is high, the probability of drawing a variable $\beta = 0$ will be high, suggesting a negative investment decision for the agent. Finally, when all of the possible investment decisions have been computed for all of the individual agents, those agents whose investment decision is positive are prevented from investing in the subsequent time-steps. Hence, in our simulator, the possibility of expanding an installation after its initial deployment is not permitted.

Modelling the investment decision-making process in such fashion ensures the deployment of some DRE units even when the viability of the DRE installations lie at the economically feasible limit (for instance when the PV prices are high or the retail electricity tariff is low), representing the behaviour of those users who are eager to invest. Likewise, this investment decision-making mechanism will prevent some agents from investing even under favourable conditions, representing those agents more reluctant to invest.

Computation of the distribution tariff

Finally, in our multi-agent system, an overall demand reduction in the DN might occur as a result of the progressive deployment of DRE units, which self-consume part of their electricity needs. Assuming that the revenues obtained by the DSO are computed as a monotonically non-decreasing function of the energy charged to the users, this overall demand reduction will cause a loss in revenue, inducing a need for adjusting the distribution tariff to offset the losses.

To adjust the distribution tariff, the following inputs are required: the net consumption of all the agents of the DN (groups A and B), and the retail electricity tariff at every time-step of the dynamical system. Then, we represent the cost recovery scheme of the DSO at every time-step by computing the potential economic imbalances created by the DRE installations deployed within the DN. If the revenue of the DSO at a particular time t does not match its incurred costs (assumed constant over the simulation horizon), an economic imbalance appears (which can be positive or negative). Thus, the adjustment of the distribution tariff must account for both the potential imbalance and the gradual aggregated net demand reduction in the system, this is calculated according to equation (2):

$$\Pi^{(dis)}_{t+1} = \frac{C+\Delta_t}{\widehat{D}_{t+1}} \quad \forall t \in \{1,\ldots,T\} \tag{2}$$

where $\Pi^{(dis)}_{t+1}$ is the distribution tariff of the next period, C are the incurred costs of the DSO, Δ_t represents the imbalance between costs and revenues at period t, and $\widehat{D}_{t+1}$ is the expected aggregated demand (kWh) of the next period.

TEST CASE

To illustrate the functioning of our multi-agent system, an example inspired by the current regulation policy in the Walloon region of Belgium is presented in this section. Hence, a tariff design based on volumes of energy traded (paid in €/kWh) is considered. Moreover, to test different environments, we use three distinct incentive schemes, based on the choice of compensation mechanism (the manner electricity traded between the DRE and the grid is recorded). The compensation mechanisms considered are: (a) net-metering (NM): this system consists of one meter that records imports (DRE ← Grid) by running forwards, and exports (DRE → Grid) by running backwards, therefore, this means that both directions are assigned with the same monetary value, namely the retail electricity tariff; and (b) net-purchasing (NP): this option consists of two independent meters for imports and exports, in this setting imports are paid for at retail electricity tariff, and exports are paid at a selling price (SP). With NM the total exports are upper bounded by the total imports, however, with NP there is no upper limit. The three evaluated cases are: *(i)* NM, *(ii)* NP SP=0.04 €, and *(iii)* NP SP=0.08 €. In the three cases the retail electricity tariff is initially set to 0.22 €.

At every time-step of the multi-agent system simulation, we keep track of the deployed DRE units, and of the distribution tariff adjustment. Thus, we can compute the evolution of the system in terms of rate of DRE deployment and distribution tariff evolution. The results of the testing of the multi-agent system with the three different environments are summarised in Figure 2.

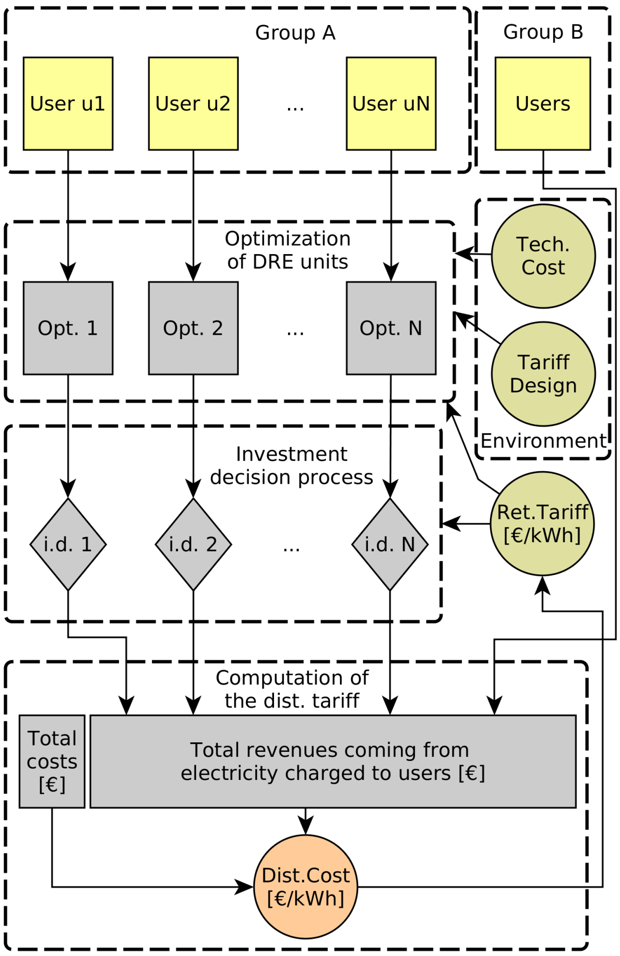

Figure 1: *Data flow diagram of the proposed multi-agent system. The flow of actions occurs from top to bottom. The individual users of group A, characterised by their load, undergo an optimisation. The optimisation requires the technology costs, the tariff design, and the retail electricity tariff, as well as the user load. The individual results of the optimisation are used by the investment decision model, which compares the LCOE of the individually optimised installations with the retail tariff, yielding a positive or negative investment decision for each potential installation. Finally, the revenues derived from the aggregated net consumption of all users of group A and of group B are compared with the (fixed) DSO costs, and the distribution cost is updated.*

This figure depicts the two metrics considered: evolution of distribution tariff (left axis) and evolution of DRE deployment (right axis), for the three cases. Regarding the distribution tariff, we observe a similar 0.02 € increase for cases *(i)* and *(ii)* after 10 years, due to the loss of revenue of the DSO in both cases, derived from the DRE deployment. This indicates that both cases are more inefficient distributing the DSO costs than case *(iii)*. As for the DRE deployment, we can observe a greater deployment for cases *(i)* and *(iii)* both in the trend and in the final outcome after

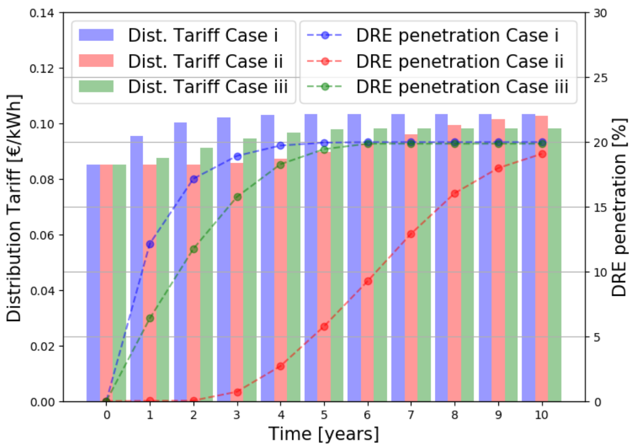

Figure 2: *Evolution of the distribution tariff (left axis) and evolution of DRE deployment (right axis). The deployment of DRE units induces an increase in the distribution tariff. Such an increase features a different extent depending on the environment (composed of tariff design, incentive scheme, and technology cost).*

the simulated period, than for case *(ii)*. This suggests that case *(ii)* is outperformed in terms of DRE deployment fostering by cases *(i)* and *(iii)*. These distinct behaviours can be explained, case by case, by the optimal solution identified by the *optimisation of DRE units* component of the multi-agent discrete-time dynamical system:

- Case *(i)*: with this environment, it results optimal to import and export the same volume of electricity so that the electricity bill is reduced (netting 0 kWh consumed). This leads to installations without batteries (since storage and grid are perfect substitutes). Eventually with this setting the DRE owners will not compensate the DSO for their grid use.
- Case *(ii)*: with this environment, imports must be reduced to decrease the bill, leading to highly autonomous installations (large PV + battery capacities). Eventually with this setting the DRE units will become completely independent.
- Case *(iii)*: by increasing the SP with respect to the previous case, the DRE owners business case is to become electricity producers, selling it to offset their electricity bills. This leads to installations with large PV capacites as well as some storage. With this setting the DRE owners still pay the DSO for their grid use, since they rely on it during periods with low PV production.

CONCLUSION

This paper has presented a multi-agent discrete-time dynamical system to describe the interaction between the distribution networks and the consumers. In such a system: (i) electricity consumers interacting with a single distribution network are modelled as rational agents that may invest in optimised distributed renewable energy installations; and (ii) the distribution tariff is adapted according to the evolution of the DSO's revenues, depending on the distributed renewable energy that is produced and consumed in the distribution network.

To illustrate the performance of the multi-agent system, we have designed and simulated three different scenarios, starting with the current regulation in the Walloon region of Belgium, and further exploring other incentive schemes. The simulator allows to illustrate the impact of the regulation policies on many aspects: (i) the evolution of the electricity distribution tariff, and with it, the evolution of the retail electricity tariff; (ii) the evolution of DRE deployment; and (iii) the optimised configurations of distributed renewable energy installations in terms of production and storage capacities.

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