The Wisdom of Sustainable Communities in the Digital Era: The Case of Efficient Energy Management

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Abstract. Wise management of natural resources has become a fundamental challenge nowadays. Cooperative approaches are needed in order to provide a sustainable framework for stimulating the individual awareness and participation towards common environmental objectives. In order to reach mutually beneficial outcomes, public administrations, companies, individuals and communities will need to organize for managing their aggregated consumption, reducing unnecessary use of scarce resources. This is especially true in the field of energy management where the bounded nature of the resources and the behavioural impact of the stakeholders on the overall system both play a fundamental role. The proposed research aims at contributing to what remains a challenging issue across disciplines: explaining the evolution of cooperation among unrelated individuals in human societies. We utilize an evolutionary game theoretic modelling framework to identify conditions under which collaboration among energy end-users mediated by information and communication technologies (ICT) will support its sustainable exploitation.

Keywords: Energy management, social contagion, bottom-up innovation, community, Web 2.0, smart electricity grids, replicator dynamics, evolutionary game theory.

1 Introduction

Local and global ecosystems are under growing pressure worldwide. Their sustainable management requires not only an understanding of the environmental factors that affect them, but also a knowledge of the interactions and feedback cycles that operate between the resource dynamics and the socio-economic dynamics attributable to human intervention. History teaches us that the livelihood of our species has been inextricably related to our ability to cooperate in the sense of restraining use of ecosystem services to sustainable levels rather than giving in to individual short-sighted resource over-exploitation. Maintaining such cooperation against the myopic self interest of the individual users and despite growing environmental pressure is a challenging task that often depends on a multitude of factors, as both successful and unsuccessful environmental management has shown. As an example, take the objectives of CO2 emission

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reduction set by the European community, which necessitate a dramatic behaviour change at the individual level.[1]

Today, household consumers perceive electricity as a commodity which can be consumed at will and in unbounded quantity. In most of the cases, the only feedback they receive takes the form of a monthly or bi-monthly bill. On the bill, many parameters contributing to the global cost are detailed such as actual or estimate consumption, corrections from earlier estimates, fixed costs, and an often complex pricing model which, depending on the country, location or utility, may include considerations such as variable pricing depending on the time or day of the week and the consumption threshold reached over a period. As a result, the effect of individual behaviour is lost. Individual monitoring solutions, if not linked with community profiling, local data conditions and energy production information, will have a limited impact due to lack of visibility and understanding on the user part.

We think that community well-being and social engagement have a strong potential for motivating behavioural change, but have not yet been fully leveraged. Therefore a holistic approach, considering all possible (hardware) elements, but also including end-users, is needed to address the energy challenges of the coming years. To achieve this goal, substantial help may come from a technology that empowers small consumers such as households as well as small and medium enterprises (SME) to actively engage them in the effort, providing the incentives and means for achieving a significant contribution to the reduction of the environmental footprint of human activities and the improvement of energy efficiency. If empowered with the right tools, energy users will strive and collaborate to define their own (community) energy saving measures and consumption models. This bottom up approach has the potential to reach faster concrete results and favour the behavioural changes. The unprecedented innovation pace happening on the Internet and characterised by the "Web 2.0" wave, demonstrates the potential of bottom-up innovation in complex socio-technical systems.

The proposed research aims at contributing to what remains a challenging issue across disciplines: explaining the evolution of cooperation among unrelated individuals in human societies. In the absence of enforcement mechanisms, conventional evolutionary game theory predicts that the temptation to act in one’s own interest leads individuals to inefficient use of resources. A growing body of knowledge, however, demonstrates that in many situations there is more to human behaviour than selfish behaviour: experimental results from behavioural economics, evolutionary game theory and neuroscience have inexorably made the case that human choice is a social experience. Recent empirical studies show that social norms significantly influence behaviour, often effectively enhancing the efficiency in resource use.

In our research we endow communities with a multi-layered technological framework that will provide them with an innovative P2P infrastructure linked with smart metering systems allowing an open, distributed monitoring and control plan for local energy grids. These, in turn, enable community-level organization of users and new services and business models. As shown by the internet, “peoples’ solutions” have the potential to reach faster and far beyond the limits imposed by political constraints and

[1] The targets for 2020 are 20% reduction in emissions compared to 1990 levels, 20% share of renewable energies in EU energy consumption; and 20% savings in EU energy consumption compared to projections.

slow societal changes. The successful implementation of this approach is conditional on the success of a collaboration model favouring the overall sustainability of the system via the uptake of the implemented solution by a substantial proportion of society members. That is to say: will such a bottom-up radical reform of the energy system develop and survive in a world divided between socially-inclined individuals as well as selfish ones? We investigate this question by taking an evolutionary game theory perspective.

More specifically, we examine the role of prosocial behaviour2 as a mechanism for the establishment and maintenance of cooperation in resource use under variable social and environmental conditions. Using evolutionary game theory, we investigate the stability of cooperation in a population of resource users (e.g. energy users) that are concerned about their status with respect to other community members and therefore are able to compensate (in a frequency-dependent fashion, i.e. to a degree related to the frequency of prosumers relative to traditional users) the losses incurred by shifting energy practices to more sustainable ones with benefits that are exclusive to the community of prosumers. That is, individuals of this idealized economy, which for the sake of concreteness may be thought of as a region or a municipality, face a trade-off: on the one hand they can continue with their business as usual, i.e. continuing to consume energy at will without incurring the costs of planning ahead of time and coordinating with other community member, or on the other hand they can shift paradigm and constraint themselves to a socially agreed upon acceptable level. By doing so, their conventional materialistic pay-off is assumed to be below that of the non-cooperating agents, to account for the above mentioned costs of coordination, but such disadvantage may be offset by a term capturing the benefits that accrue to prosumers only by belonging to the sustainable community. Such benefits have a magnitude that depends on the relative size of the community, since, as will be further explained in the next section, to take full advantage of the new paradigm, it is assumed that many participants should be involved; in other words, at low frequencies of prosumer types, the defectors, i.e. those that opt out of the technological and behavioural agreement (to be described below), will be better off, but at high enough frequencies of cooperators (prosumers), the latter will enjoy benefits that will make it advantageous to be part of the community.

To recapitulate, we model two types of agents: cooperators (prosumers) that restrain their energy usage level to a coordinated and socially accepted amount that is closer to the efficient level for the community, and defectors who base their consumption decisions solely on their immediate needs in a own-regarding way. The prosumers' pay-off from resource use is augmented contingently upon both the pay-off difference with respect to the defectors (a larger one signals greater divide between the groups and consequently a greater cohesion among cooperators) and the benefit function, which is increasing in the frequency of cooperators (as the advantage of belonging to the group can be reasonably assumed to be higher the larger the group is in relative terms).

When sufficient levels of social and technological benefits accrue to those enforcing the social norm (innovative and well coordinated emission-reducing energy practices), cooperation obtains, leading to a sustainable resource management. We analyse whether coexistence of both norm-observing and norm-violating types is possible, and

[2] See Gowdy (2008), Tavoni (2009) and the references contained therein for an exploration of social value orientations and other-regarding preferences.

to what extent it depends on the social and ecological environments.This approach allows us to better explore the interactions between the environmental and the socio-economic dynamics, and their response to endogenous (i.e. behavioural) as well as exogenous (i.e. climatic) pressures exacerbating the resource unpredictability.

This study is meant to contribute to the literature by providing a systematic exploration of the resilience of coupled social-ecological systems to local and global change, by allowing the evaluation of the impact of shocks in energy dynamics on resource use and, more generally, on the capacity of the users to adapt to uncertainty in resource availability. At the behavioural level, this framework is well versed for analysing the role of information and communication technologies (ICT) in changing the energy consumption behaviour of people and local communities towards more sustainable practices. The question we have in mind is: Under which conditions will a community of energy-aware individuals thrive? In order to address it we will present an example of how we picture such a sustainable community in section 2, while section 3 will present the evolutionary game-theoretic model based on replicator dynamics, followed by a section containing conclusive remarks.

2 Enerweb as an Example of Efficient Energy Management

In our research, we aim at leveraging the concept of community to create a sustainable solution for the energy grid. In fact, in order to successfully address global warming, there is a need to devise radical innovations in the manner energy is managed. The European Commission has identified two important conditions and challenges that need to be solved in order to provide systemic results. The first one is to foster energy efficiency and savings by engaging users in participating actively to the reduction of the global carbon footprint. The second is to increase the penetration of renewable energy sources in the market.

We propose an innovative approach (from now on labelled enerweb) that enables the raise of bottom up energy wise communities and the operation of prosumers (users who can also act as micro-producers) and virtual operators that obtain access to the electricity grid and enter the market to trade the power they generate. These new producers and community traders would be working at relatively low voltage and be distributed in several locations, in the vicinity or within urban or suburban areas. Several collaboration and partnership models with the local distributors would arise, with the final result of lowering the entry barriers, thus letting prosumers become part of a global socio-ICT ecosystem, where they can negotiate the energy they produce and consume.

Enerweb is therefore a socio-technical environment engineered as an open, secure, resilient and scalable service oriented infrastructure built on the P2P paradigm for the management of the local smart grid and its customization and extensibility towards multi-utilities management and control. It offers an Open Standards and Open APIs infrastructure that allow all the energy value-chain stakeholders to manage energy-related data and communication. It acts as the information aggregator between all elements of the network for their monitoring and control and will constitute the technology backbone which will enable the enerweb community concept to work properly. Enerweb offers self-optimization mechanisms to help organising large-scale unstructured networks

Fig. 1. Sketch of the proposed framework

of small devices into well-defined geographical groups that optimise resource allocation to save time and energy while preserving the network stability in case on changing energy conditions. It also offers an intuitive user interface that will provide users with all the necessary community information aspects and options for actions.

In this framework incentive policies play an important role in shaping user behaviour and ultimately achieving performance gains. We intend to study several possible incentive policies that will help the prosumers organize in communities and more generally promote cooperation. Current incentive strategies are summarized in low cost energy offers for overnight use. An example of more complex incentive strategy would be to offer cheaper prices for electricity provided in low variation levels. This would motivate prosumers to organize in communities in order to coordinate and normalize the collective power profile.

Enerweb would allow reducing the lack of involvement of consumers in the energy saving efforts. We believe that pure monetary considerations are insufficient to induce a behavioural change among consumers. Several propositions have been made to address this problem through, e.g., market mechanisms with real time pricing or using real time monitoring to improve the accuracy of the feedback. However, while such initiatives contribute to making monetary incentive more effective, they do not address the root of the problem, namely, that other forms of incentives are needed. Considering Europe, where the average income is relatively high and electricity represents a small fraction of household expenses (significantly below 10%), monetary incentive will remain insufficient to motivate dramatic behavioural changes until energy prices dramatically increase – in other words, until it will be too late.

In fact, in contrast with modelling efforts highlighting the role of agents' selfishness and sole concern for economic incentives, we consider user motivation in all its social relevance (as captured by the prosumers' benefit function). Users are given the option to self-organize into groups (communities) of various sizes, with broad freedom in determining how far they are willing to commit and reduce green-house gas emission. Instead of relying on selfish interest (e.g., through monetary incentive) or top-down infrastructure development, the enerweb will promote collaboration among users (forming dynamic communities), the design of innovative solution and the fulfilment of greater common objectives. For achieving their objectives, these communities express concrete and measurable targets regarding, in particular, their joint electrical consumption.

A mix of selfish and altruistic interests such as environmental concerns or cost reduction, possibly further motivated by specific governmental incentives is driving the behaviour of the prosumers. Communities provide many potential benefits to the prosumers themselves as well as to the European and global power system. These benefits include greenhouse gas emission reduction, energy saving, promotion of renewable energies and direct economic gains to the energy users. Prosumers, while incurring higher costs relative to the non-cooperators due to the adoption of new technology and constraints imposed by the goal of reducing emissions and coordinating efforts, are also able to gain financial benefits (potentially greater than the incurred costs of cooperation) as they participate in energy transactions within the group at more favourable conditions than in the outside energy markets, given a relatively high level of participation. Through self-organisation, for example, prosumers are able to actively affect the group energy balance and be actively involved in day-ahead energy planning. Socially-oriented behaviour among individuals with common motivations and interests (e.g., environmentalists) is also expected to emerge, positively contributing to the benefits enjoyed by the community members.

3 Lessons from a Game Theoretic Model of Bounded Rationality

Agents are considered as productive units (one can think of an agent as an individual or a family). Their source of revenue is assumed to positively depend on two factors: the availability of an indispensible resource for both productivity and livelihood, such as energy broadly conceived, and the amount of effort agents put in their productive (income-generating) actions, which itself is an increasing function of the energy abundance. That is, both the energetic resource and the (energy-absorbing) work effort enter in the agents' (twice-continuously differentiable) "income production function" $f(E, R)$, where E represents the community effort (e.g. the aggregate energy consumption) resulting from the actions of the n agents, and R is the resource available to the community (e.g. the available energy level, which may either be entirely consumed in a given time period, or saved in part for future consumption). Formally, letting e_i be the individual effort (loosely speaking his/her carbon footprint), which can either take value e_c for a prosumer or e_d for a traditional energy consumer ($e_c < e_d$ due to the more sustainable practices of the former), the following inequalities are assumed to hold:

$$\frac{\partial e_i}{\partial R} > 0\,,\ \frac{\partial f(E,R)}{\partial E} > 0\,,\ \frac{\partial f(E,R)}{\partial R} > 0\,,\ \frac{\partial^2 f(E,R)}{\partial E^2} \leq 0\,,\ \frac{\partial^2 f(E,R)}{\partial E\,\partial R} \geq 0\,,\ \frac{\partial (f(E,R)/E)}{\partial R} \geq 0.$$ [3]

[3] These assumptions are generally employed in the literature concerning resource exploitation in a common pool resource, such as, for example, a fishery where a community of fishermen have access to it and each can decide on the individual level of exploitation (jointly affecting the sustainability of the resource utilization). Given the similarities we have drawn between this type of community operating in a traditional ecosystem with the one considered here and its relationship to the environment and the socio-ICT ecosystem, we believe the assumptions to also be plausible in the context of this paper.

Let's go in further detail about the model. It is useful to consider again the joint level of effort E resulting from the actions of the n agents choosing their level of effort e_i; letting $f_c \in [0,1]$ be the proportion of cooperators (prosumers), we have $E(f_c, R) = f_c * n * e_c + (1 - f_c) * n * e_d$. We assume that f_c is continuous and non negative and note that for positive levels of e_c and e_d, the total level of effort is a decreasing function of the frequency of cooperators.

The two effort levels, that are here assumed to sum up the behavioural inclinations of all agents in the community, are bound below by the efficient resource use level and above by the static Nash equilibrium level. This amounts to require that both agent types follow practices that are above those that would maximize collective utility, but to a different extent: the traditional energy users ignore the emergent social norm prescribing the socially agreed-upon effort e_c by choosing a greater level e_d (up to the individually rational but inefficient Nash equilibrium level resulting in resource overuse), while prosumers stick to e_c, which, as a special case, may coincide with the level that efficiently trades off the individual incentive towards high or uncoordinated energy utilization with the social need to impose constraints to guarantee a sustainable resource use (which ultimately benefits the individuals). Letting E_{eff} be the community efficient level, and $e_{eff} = \frac{E_{eff}}{n}$ the corresponding individual efficient level, and e_{nash} be the Nash equilibrium level of effort, we formalize what stated above as: $e_{eff} \leq e_c < e_d \leq e_{nash}$.[4] These conditions guarantee that, at the aggregate level, positive rents from productive use of the energetic resource can be maintained. That is, the average product of labor is assured to be above the opportunity cost of labor independently from the share of defectors, providing the incentive for agents to increase their energy consumption (as they can earn positive profits for positive levels of effort). It is further assumed that $f(0, R) = 0 = f(E, 0)$ for the obvious reason that strictly positive levels of energy and resource are required to generate income via the function $f(E, R)$.

An example of a function satisfying the above conditions is the familiar Cobb-Douglas formulation with decreasing returns to scale: $f(E, R) = E_t^{\alpha} * R_t^{\beta}$, $\forall E \geq 0, R > 0$ and $\alpha + \beta < 1$. These well-behaved functions guarantee the existence of an optimal solution to the aggregate payoff maximization problem: $\exists!\ \text{argmax(aggregate payoff)} = E_{eff}\ \text{s.t.}\ f'(E_{eff}) = \frac{w}{p}$, where $\frac{w}{p}$ is the ratio between the opportunity cost of labour w and the market price p of the energy-demanding good produced.

We know that the aggregate level of effort in equilibrium if all agents play according to the Nash equilibrium will be above E_{eff} as each individual will consume more energy than is efficient.

[4] Note that a direct implication of such constraints is that $E_{eff} \leq E \leq E_{Nash}$. See Dasgupta and Heal (1979) for a pioneering contribution on exhaustible resources.

Let's turn to the resource dynamics and its interaction with the social dynamics occurring as a result of human action. On the one hand we account for a positive rate of growth of energy, as confirmed by current data on production.[5] In order to consider the entire picture, however, we must include the function $\mathrm{f(E, R)}$, which depicts the aggregate energy use by the individuals. Formally,

$$\dot{R} = r(R) - f(E,R) \tag{1}$$

Where $\mathrm{r(R)}$ is the energy growth rate (in the absence of usage) and $\dot{\mathrm{R}}$ indicates the time derivative of the resource stock, i.e. the overall energy growth rate resulting from the interaction of production and utilization. Note that the energy creation side, which is captured by the first term in the right-hand side of (1), is exogenous with respect to the frequency of prosumers ($\mathrm{f_c}$), which affects instead the second term (representing the energy consumed by the community for productive tasks). For the sake of simplicity, in this paper we assume the resource stock R to be constant and equal to an exogenously fixed level $\overline{\mathrm{R}}$; that is, we focus on communities whose demand for energy is small relative to the energy production side. This framework, however, can easily be extended to model bigger actors whose collective action may result in an imbalance between energy growth rate and community usage due to overconsumption.

With these notions in mind, we are now ready to shift attention to the strategies and tradeoffs faced by (non.cooperative) traditional consumers and prosumers.

The individual payoff given resource $\overline{\mathrm{R}}$ and the behaviour of all community members is given by:

$$\pi_i(e_1, e_2, \dots, e_N) = p\frac{e_i}{E} f(E,\bar{R}) - we_i \tag{2}$$

Equation (2) applies to all individuals, independent of their types, as it represents the amount they can make "in isolation", i.e. without the help of fellow community members. This amount is proportional to the aggregate payoff, in relation to the individual's energetic uptake $\mathrm{e_i}$, which enters positively in the first term in the right hand side of (2) and negatively in the second term representing the work-related costs. To account for benefits that accrue solely to the prosumers (see section 1 and 2 for the rationale behind these cooperator-exclusive benefits), which may offset the disadvantage inherent in their more sustainable energy utilization depending on the relative abundance of cooperators, we introduce equation (3):

$$\begin{aligned}\mathcal{U}_i = \pi_i + \omega(f_c) * max\{\pi_d(E) - \pi_i(E), 0\} = e_i\left(p\frac{f(E,\bar{R})}{E} - w\right) + \omega(f_c) * \\ max\left\{(e_d - e_i)\left(p\frac{f(E,\bar{R})}{E} - w\right), 0\right\}\end{aligned} \tag{3}$$

Note that the above equation boils down to $\mathcal{U}_c = \pi_c + \omega(f_c)(\pi_d - \pi_c)$ for the prosumer and $\mathcal{U}_d = \pi_d$ for the traditional energy consumer (defector). While the latter

[5] The 2008 Observ'ER inventory on electricity production in the world reports a 3.5% growth rate over the 1997-2007 decade for total production, with a 3.8% growth rate for conventional production and a 2.6% rate for renewable electricity production. The yearly 2006-2007 growth rate is estimated at 4.5% overall, with conventional production growing at a 4.7% rate and renewable production at 3.6%.

can only count on their productive activities to generate income, the former can also tap in the community. As participation in the Enerweb is voluntary and observable, these benefits are denied to non-members; further, it is assumed that the community benefit function $\omega(f_c)$ is increasing and concave in the number of participants. Notice also that it multiplies the payoff difference between defectors and cooperators, as the cohesion of the prosumer group will be higher the biggest the reduction in energy consumption they undertake to be sustainable (leading to a larger negative productivity gap with respect to traditional energy consumers).

For explanatory purposes, consider the following functional form for the prosumer reward function: $\omega(f_c) = f_c^{\lambda}$. Graphically, for two distinct values of λ equal to 0.2 and 0.5, it would yield the following:

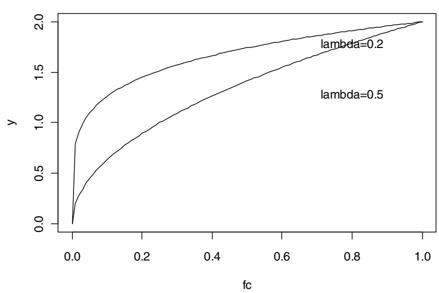

Fig. 2. The community reward function and its dependence to the frequency of cooperators

The analysis of the behavioral evolution of agents facing decisions on their energy practices is conducted by means of replicator dynamics. By so doing, we avoid the complete rationality requirements typical of models of optimization, while retaining some convergence towards the imitation of successful behavior. Agents, rather than rationally best responding to the actions of others as in Nash equilibrium, update their strategies when given the option, and switch to the strategy of the agent with which they are randomly matched if the utility of the latter is above the individual's[6]. It can be shown that such strategy revision takes place with a probability which is proportional to the payoff difference with respect to the average: if, for example, the latter is well above the payoff of a cooperator, he or she is more likely to notice the need to switch than if the average was only slightly above the agent's payoff.

Formally, this leads to:

$$\dot{f}_c = f_c(U_c - \overline{U}) = f_c(1 - f_c)(U_c - U_d) =$$

$$= f_c(1 - f_c)(\pi_D - \pi_C)(\omega(f_c) - 1) \qquad (4)$$

[6] See Taylor and Jonker for their pioneering work on the replicator dynamics.

Again the dotted superscript stands for time derivative: equation (4) models the evolution of cooperating types. We are interested in the nontrivial stable solutions, i.e. those in which positive amount of both types coexist (with $f_c \neq 0$ and $f_c \neq 1$).

4 Conclusions

One of the main conclusions that we have derived by looking at the steady states of the dynamic system given by (1) and (4) is that coexistence of prosumers and traditional consumers is stable for a wide region of parameters. We are in the process of complementing the analytical results obtained by this and other variations of the stylized model proposed here with more detailed agent and resource characteristics by means of agent-based simulations. This will allow us to get more specific insights into the research and policy questions that need to be addressed if one takes seriously the paradigm shift needed to cope with today's energetic and climatic challenges.

Bottom-up approaches may prove to be one effective way to revolutionize current energetic practices; however technological and societal barriers may discourage the spread of adoption. The recently published UKERC Energy 2050 project [15] states that "Microgeneration offers a radically different approach to meeting energy needs, but capital cost and performance are currently barriers for many technologies. However, it could be important in meeting future residential heating needs, and could help catalyse change towards low carbon lifestyles". Our theoretical effort supports this view.

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