POLICY-ORIENTED ENERGY SYSTEM MODELING WITH *XEONA*

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ABSTRACT

Energy systems exist to provide industry, commerce, and households with fuels and energy-services. In addition to financial cost and reliability imperatives, these systems are now being asked to perform across a range of sustainability criteria. Most national systems fall well short on this second count and governments need to promote a suitable transition. Market liberalization over the last 20 years has made this task more challenging in public policy terms and yet could provide good incentives for innovation, reinvestment, and user responsiveness, given the right institutional measures. The development of suitable public policy may necessitate sophisticated simulation techniques, particularly considering the technical and commercial complexities involved, the multi-criteria nature of the policy problem, and the fact that most interventions will interact.

This paper presents *xeona* (extensible entity-oriented optimization-based network-mediated analysis), an object-oriented simulation environment designed for such use and currently under development. The modeling ethos is to represent important entities from the problem domain as elements within the simulation domain. Hence a *xeona* model is built from the ground up using the technical plant, controllers, markets, actors, and policy measures that exist in reality or are under consideration. The presence of actors allows low-stake commercial and domestic decision-making to be embedded within the model and thereby drive system evolution in response to commercial pressures and proposed policy interventions.

Model construction is one aspect, but the specifics of policy usage and interpretation are also important. To this end, a technology evaluation issue involving neighborhood fuel cell cogeneration in northern Europe is briefly illustrated with numerical results.

Keywords: complex systems, energy policy, entity-oriented modeling, network dynamics

INTRODUCTION

There is a growing interest by governments and the informed public alike in the role that proactive energy policy might play in promoting a transition to more sustainable energy systems. Energy policy formation is a complicated exercise involving institutional issues as diverse as international treaties, environmental law, market design and regulation, government support, mandatory standards, research funding, and the dynamics of technology innovation and uptake. Nowadays energy policy needs to be evaluated across multiple public interest criteria, including cost-competitiveness, carbon mitigation, energy security, system resilience, and any number of social factors. The underlying technical and commercial systems are now recognized as complex in nature. And the contexts in which such systems operate are increasingly volatile in both economic and environmental terms.

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Many of the established energy policy analysis methods are unable to perform in such circumstances and a number of new strategies are being developed to address some of the more evident shortfalls. One of these strategies makes use of highly disaggregated and relatively literal simulation techniques.

This paper reviews *xeona* and its underlying design. More specifically, *xeona* is a policy-oriented energy system modeling environment currently under development by the authors (however for convenience, the paper is written as though the software is complete). It is both *high resolution* and *bottom-up* in the sense that each plant, connection, actor, decision, and transaction can be depicted if deemed important to the problem at hand. *xeona* supports supply contract competition and nodal market pricing.

Simulations of this type fall under the complex adaptive systems (CAS) paradigm. In the case of *xeona*, a subset of this paradigm is used which might be best described as a dynamical networked systems approach with market and non-market coordination/control protocols and explicit endogenous *low-stake* decision-taking. Conversely, *high-stake* decision-making (for instance, commissioning a major power station) is left as an exogenous input for the modeler to specify prior to or during runtime — that is, as a *fixed* or *interactive* scenario, respectively.

xeona combines sophisticated actors with a rich technology depiction. These actors exhibit *bounded rationality* — which means that, for example, house owners take decisions in a natural way, consistent with their rationality type (related to temperament) and social milieu (related to social status and value orientation). The technology description is likewise based on a consideration of reality and incorporates *context-dependent technical performance* covering plant efficiency, capacity, and cost formation.

The term *actor* is used here to describe decision entities who interact relatively infrequently and warrant a sophisticated decision model. Whereas *agent* is reserved for entities which interact often and tend to make more spontaneous decisions. Hence the somewhat unusual term *actor-based modeling* is adopted.

xeona supports *numerical optimization* where it exists in practice or is under consideration. For instance, a facilities operator can assign unit (plant) commitment based on minimized short-run marginal cost (SRMC) or minimized direct CO_2-e (carbon dioxide equivalent) emissions. Nodal markets based on linear programming (LP) can be similarly included [1]. As will be seen later, *xeona* embraces the idea of *distributed management*.

This style of simulation has been called *entity-oriented* (EO) modeling due to the fact its underpinning ethos is for all relevant entities in the problem domain to be represented in the simulation domain in relatively concrete form — an approach made feasible by object-oriented programming [2, 3].

EO modeling is particularly suited to distributed systems operating in variable circumstances. In such arrangements, network dynamics tend to be a preeminent issue [4]. Briefly, *network dynamics* are the effects and externalities that arise from the capacitated nature of networks and the benefits of membership, respectively. These characteristics impose demands on network coordination and drive recruitment in ways that can be difficult to anticipate without numerical modeling.

The concept of an energy system is accorded a broad interpretation and is defined in terms of purpose. In all but a few specialist circumstances, the *purpose* of an energy system is to supply exergy-services.[1] *Exergy-services* are amenities that are either provided through exergy consumption *or* could have been supplied thus. Hence, the scope of such systems normally extends well beyond the boundaries encompassed by commercial transactions. Examples of exergy-services include: space and water heating, illumination, food and timber drying, and motive power applications.

xeona can be applied and interpreted in a variety of ways [5]. The most adventurous mode is evolutionary, whereby a given simulation is triggered and left to evolve under endogenous low-stake and exogenous high-stake decision-taking. Less ambitious application modes include non-evolutionary simulation and comparative analysis.

xeona itself does not directly prescribe a set of overarching policy goals. But concerns over *climate protection* [6] and *long-run energy security* are certainly

[1] Readers unfamiliar with the term *exergy* can substitute the word *energy* in its colloquial sense. Both indicate the potential of a resource to provide thermodynamic work, although energy tends to be restricted to recognized fuels.

topical, with the Kyoto Protocol having entered into force in early-2005 and the issue of *peak oil* [7] gaining attention. In addition, and given sufficient structural detail, local public interest issues, such as *air pollution load*, can be tallied for policy support — and even constrained or locally minimized. Moreover, *xeona* does not posit perfect markets and can provide a platform for examining *pricing regulation* and *market design* in the presence of strategic commercial behavior.

Some matters of usage conclude this introduction. The phrases *energy system* and *exergy-services supply system* (ESSS) are taken as synonymous. The term *plant* is used in its most general sense and, for instance, would include those features of a house which contribute to thermal comfort. The term *fuel* is also accorded a broad meaning and covers electric power, heating and cooling utility, and carbon dioxide sequestration. The term *intensity* refers to a quantity associated with a resource which remains independent of scale, examples might include: unit price, specific carbon content, and *flo* and *return* temperatures. A *graph* is mathematical structure suitable for depicting networks [8].

RELATED WORK

As indicated, *xeona* combines actor-based modeling and high resolution technical simulation.

Most of the policy-oriented actor/agent-based simulation projects to date have focused on the electricity industry, either to investigate industrial organization or market behavior and abuse. This research orientation is no doubt related to the economic importance of the sector and the fact that liberalization has thrown up a number of counter effects, such as: circular asset valuation (whereby pricing drives valuation and *vice versa*), zonal market power (where network saturation within nodal markets confers dominance), and strategic pricing (more particularly to defend incumbent grids from encroachment).

Actor/agent-based modeling has been used to investigate structural consolidation within the German electricity industry [9] and to scrutinize participant behavior within primary electricity markets in North America [10], Australia [11, 12, 13], and elsewhere.

High resolution technical simulation has played a very limited role in energy policy analysis thus far [4]. That said, European initiatives to better understand neighborhood cogeneration and district heating are starting to employ this approach [14].

The CAS paradigm — or, more precisely, its actor/agent-based and high resolution subsets — is not the only methodology being applied to support *energy policy formation* [15]. Other paradigms (with examples) include: planner-oriented structural optimization [16], system dynamics [17], econometric [18], general equilibrium [19], dynamic input/out [20], optimal growth [21], and climate policy integrated assessment [22] — with many now seeking to better represent technological change [23] and (as necessary) climate issues. Note that these different methodologies can be successfully mixed in some but not all cases. Work in Japan to combine energy system models with other policy models and projections through the AIM suite [24] warrants mention. Integrated analysis based on multi-level control is also emerging as a research theme [25]. More broadly, the notion of using actor/agent-based modeling for investigating social and economic systems is described in [26]. *xeona* also shares some similarities in approach and application with urban development microsimulation [27].

XEONA

xeona has been formulated to be more general than the electricity industry models indicated previously. Key publications include [4, 5, 28].

xeona builds on an earlier high resolution technical modeling environment called *deeco* [29] which was released in 1995 [30].[2] *deeco* remains in active use and development and is well suited to single operator jurisdictions where volatile operation and non-financial additionality considerations (such as carbon mitigation) also apply.

An early application of *deeco* found that sets of technical measures are likely to interact in an adverse way — meaning that the individual contributions are sub-additive. In such cases, the design task becomes one of identifying those configurations which give the least compromised outcome [31] — a result which also has implications for policy-makers [32].

xeona is built around three conceptual layers comprising primarily *actors*, *plant*, and *zones*. Actors

[2] See: `http://www.iet.tu-berlin.de/deeco`

are grouped by *legal entity* for the purposes of individual analysis and reporting. Likewise, plant are grouped by *control domain* for the purposes of single operator unit commitment *or* market clearing and dispatch. Each plant is associated with at least one actor. Zones supply *context informatio*n to actors and plant, thus providing a backdrop covering the prevailing physical, commercial, and institutional conditions.

These ideas are broadly indicated in Figure 1, in a scheme that bears some resemblance to arrangements in New Zealand.[3] In practice, many of plant depicted would be composed of other plant. A low-stake investment option might be to extend the photovoltaic (PV) panel area, perhaps in response to some institutional incentive.

The *technical layer* is structured around the processing of resource stocks and flows, much as is discussed in [29]. Individual unit commitment is multi-dimensional for multiple fuel and/or product processes (including cogeneration). The resource flow conventions adopted for *xeona* are shown in Figure 2, with reverse (or negative) flow now supported. Mandatory and optional sinks and sources are represented by equality and inequality constraints, respectively.

Interconnected control domains are interfaced by *gateways* which pass across the required demand and intensity information. Each gateway is associated with one or more *legal contract*, covering, for instance, connection and supply (banded tariffs are supported) or market participation (through electronic auctioning). In this latter case, the market operator clears price and quantity using forward projections (two hours ahead, say), while the independent system operator (ISO) manages technical dispatch. In more basic models, these two functions can be treated as one in the same.

The control domains form a *control domain graph* (CDG) which is solved sequentially in topological sort order, as shown in Figure 3, for each interval. Hence, the CDG must be directed acyclic [8] in terms of demand transfer — rather than resource

[3]New Zealand has a number of attributes that make it interesting in relation to the development of sustainable energy policy modeling techniques. These include: island status, an unparalleled renewable resource base, an institutional preference for deregulation, significant network characteristics, and pressing infrastructure renewal decisions.

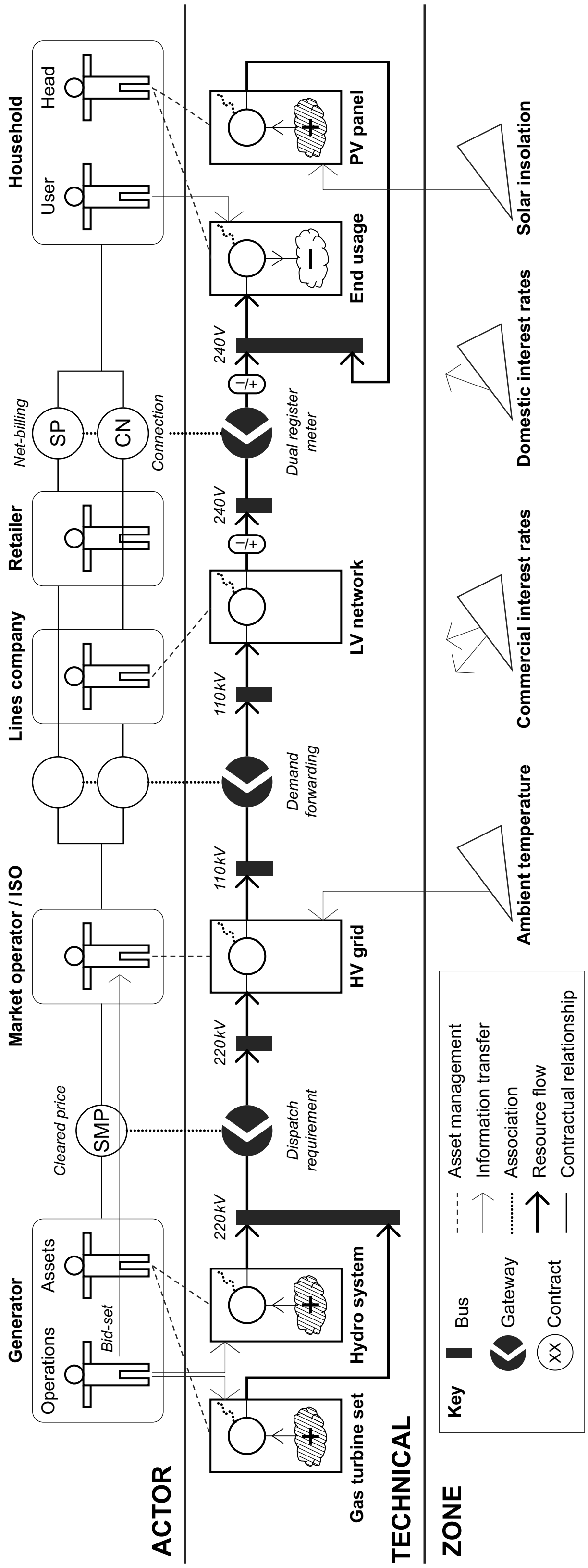

Figure 1: Three-layer diagram showing some of the key abstractions employed by *xeona*.

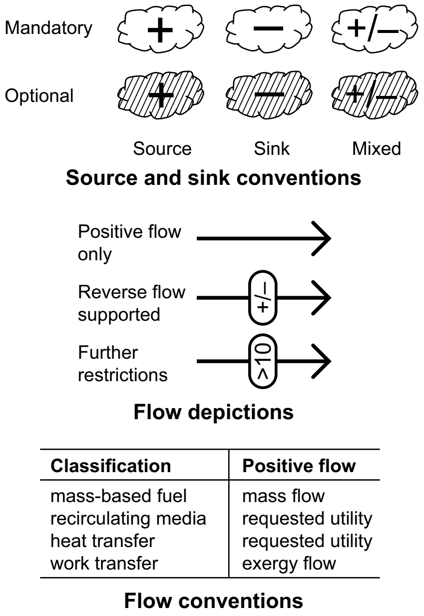

Figure 2: Resource flow conventions for *xeona*.

flow which cannot be guaranteed to be anti-parallel. Moreover, it is the demand for exergy-service and/or fuel provision that *drives* this model — a situation entirely consistent with the purpose of system definition introduced earlier.

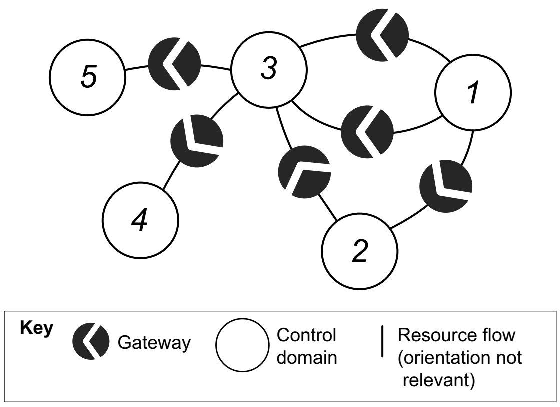

Figure 3: Control domain graph (CDG) with an acceptable solution order indicated.

The *actor layer* facilitates commercial interactions — as enabled by a particular scenario. Actors might therefore participate in nodal markets or purchase publicly posted supply contracts, technical equipment, and third-party services. Actors may also be placed in an *acquaintance network* (not shown) to facilitate bilateral negotiations.

The *zone layer* is where public policy interventions would normally be specified and where extreme external events can be defined. Given a sufficiently sophisticated model, *xeona* would be able to estimate the effects of anticipated climate change on existing and revised exergy-services supply systems.

xeona operates over various *timeframes*. Intervals typically span half or one hour, investment decisions might be revisited every three months or after key events, and scenario horizons may range from a year to a decade or more.

Space considerations meant the following design topics have either been skimmed over or omitted: exergy-services modeling (yielding fuel usage), logical flow and thermal intensity setting (including *flo* and *return* states), plant performance (including context-dependency), optimized shutdown-mode unit commitment (using mixed-integer linear programming), infeasible status responses (including relitigation and rationing), closing inventory matching (for comparative analysis), and the use of dynamic data structures and algorithms (to enable runtime intervention).

In terms of software licensing, both *xeona* and *deeco* are open-source.[4] This permits modelers the freedom to evaluate and develop the source code as they see best.

ACTOR DECISION-MAKING

Decision-making within *xeona* falls under several categories. *Operational* decisions cover unit commitment and market bid-set formulation, while *structural* decisions include plant investment and decommissioning. *Low-stake* decisions are taken within the model using context-specific algorithms, whereas *high-stake* decisions must be supplied externally, either as part of a fixed scenario or during runtime by including human subjects in the decision loop.

Low-stake structural decisions are based on the bounded rationality approach described in detail in [33]. Unit commitment is also low-stake, but relies on nominated protocols such as merit order and/or short-run optimization. Market bid-set formulation is low-stake as well, but has yet to be investigated in

[4] Both projects use the GNU GPL license together with requests to forward code changes to the principal authors and to not redistribute the codebase through anonymous download.

detail — there is, however, a growing literature on this topic [13, 34].

The term *bounded rationality* is used to describe actor decision-making which sidesteps the doctrines of (Bayesian) maximized subjective expected utility and discounted profit stream [35, 36]. And instead recognizes that actors, be they domestic or commercial, have limited knowledge, limited information gathering and processing abilities, and different preferences and perceptions as to future states of the world. Furthermore, actors may take decisions traversing only a subset of the information they hold. Researchers are currently attempting to understand this decision behavior and the particular environments in which it is exhibited. Their resultant models use simple search, stop, and decision rules. As an illustration, *satisfying* is a strategy in which one simply accepts the first decision option encountered that meets current aspiration levels.

POLICY SUPPORT

xeona supports energy policy formation from two distinct directions. First, the overall system performance is reported in terms of key public interest criteria — typically system financial cost, CO_2-e emissions, and depletable (fossil) resource use — thereby enabling informed policy decisions to follow. These results are normally presented using two and three dimensional *trade-off diagrams* [29]. And second, sets of specific policy measures can be embedded in particular scenarios and tested *in situ* against the aforementioned criteria. Such measures can range from: direct financial support, eco-taxation, feed-in laws, accelerated write-down, mandatory performance standards, and point-source air and thermal pollution discharge restrictions [5].

A key premise in this paper is that ESSS development trajectories can be affected by seemingly minor network dynamics in a manner comparable to the *butterfly effect* in long-range weather systems.

Providing insight into the way in which energy systems might be prompted to evolve from their present state is crucial when thinking about pathways to energy sustainability. It is necessary, but not sufficient, for analysts to identify socially beneficial transitions using, say, climate policy, dynamic general equilibrium, or system dynamics models. Such transitions will almost certainly need to be driven by specific policy measures — and their detailed evaluation provides a potential role for EO modeling. In short, both a roadmap and steerage are required.

This paper proposes two analytical roles for EO modeling — which can (and perhaps should) be dealt with jointly. One is examining the contribution that identified energy efficiency responses can make and how governments might best incentivize their uptake. And the other is studying the linkages between commercial strategic behavior, system evolution, and sustainability improvements.

EMBEDDED USE

There is a further reason for developing entity-oriented simulation techniques. It is likely that future energy systems will be strongly *status-aware* in order to respond to changing circumstances in an intelligent way. This means that sections of the system (probably by control domain) may need to embed a suitable localized high resolution simulation which can cast forward hours and days to analyze and offer adaptive responses. One such action might be the online auctioning of demand deferral.

DISTRIBUTED TECHNOLOGY EXAMPLE

The following example from southern Germany shows how high resolution modeling can be used to assess the attractiveness (or otherwise) of distributed technology deployment from the point of view of both a new entrant *and* the wider public interest.

The study [4, 37] looks at the merits of installing 200 kW_e natural gas-fired PAFC (phosphoric acid) fuel cells, which supply — in parallel with peak-load boilers and other measures — heat and power to low-rise apartment blocks. These various schemes compete with district heat and electricity from the incumbent municipal utility. The study also considered potential network interactions with renewable energy opportunities, in this case, solar themal systems with seasonal storage and local wind-farms. Representative results are summarized in Figure 4. One conclusion is that the multi-criteria performance of technology groupings of this kind are strongly sensitive to the quality of local integration. Even so, in this particular situation and given

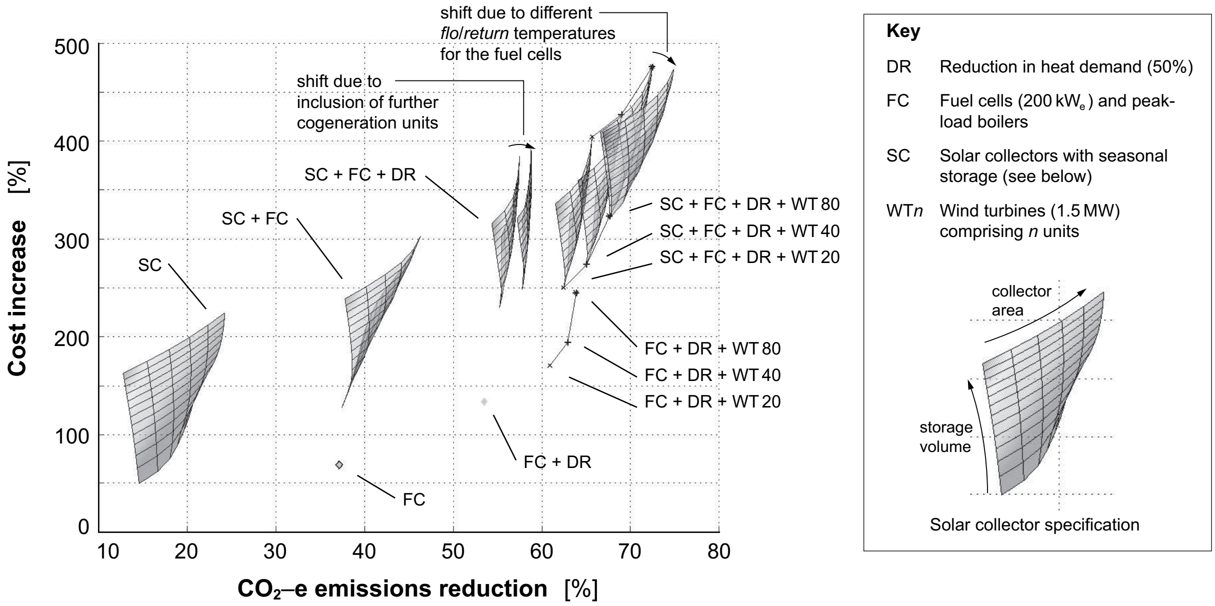

Figure 4: Relative carbon and financial additionalities for 200 kW_e neighborhood fuel cells operating in a range of configurations and control settings. The overall system performance, when combined with other local renewable energy and/or demand reduction opportunities, is also indicated. *Source*: [37, fig. 7.5]

the projected costs and other scenario assumptions, none of the options tested qualify as fully commercial propositions — despite positive social externalities. Hence, this form of modeling can provide a useful test-bed on which to evaluate policy measures designed to support low-carbon technologies.

DISCUSSION

Highly disaggregated and relatively literal energy system simulations — as exemplified by *xeona*— represent an emerging field. Many of the building blocks are still being sketched in and thus yet to be verified and accepted. However the tangible nature of these simulations lends confidence to this venture. And despite being detail intensive, entity-oriented (EO) models should not be fundamentally difficult to calibrate. Other model types, by contrast, often require abstract causalities to be estimated (for example, demand elasticity and feedback delay) and can be quite sensitive to inaccuracies.

EO models capture network dynamics naturally. This means that such models are particularly suited to system architectures and institutional arrangements where these dynamics are likely to develop. Most, if not all, energy efficiency propositions would fall into this category.

EO models maintain a clear separation between the private and public realms. This will avoid, for example, controversy over the choice of a single discount rate — because each actor, together with the public policy-maker, can be assigned an appropriate figure.

Financial cost-effectiveness should continue to be seen as a sustainability issue. This is because non-financial performance will invariably be traded off against financial cost, either explicitly or otherwise.

Such models also provides a useful qualitative description of energy systems and policy issues. This may not appear significant to the modeling community, but policy-makers and analysts often struggle to conceptualize complexity. Having access to a simplified but representative proxy model of the underlying system could assist in this regard.

Previously unreported work includes the concept of a control domain graph and the application of bounded rationality techniques to low-stake consumer and commercial energy efficiency investment decisions. The ability to include explicit decision-making in policy models appears to be a useful step. A number of current energy modeling initiatives attract criticism because they contain too little sociology — in many respects, *xeona* represents an attempt to rectify this shortcoming.

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