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ANALYSIS

Public policy modeling of distributed energy technologies: strategies, attributes, and challenges

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Abstract

The systems which provide active and passive energy-services are undergoing rapid institutional, commercial, and technical change. As part of this transformation, distributed energy technologies are expected to play a greater role. In addition, governments and local authorities are seeking to encourage selected distributed technologies, including wind power and cogeneration, for reasons of public interest. Even so, most energy sector policy support models have difficulty realizing distributed technologies, particularly where complex component/system interactions arise. High-resolution modeling addresses these shortcomings through increased topological resolution, greater temporal disaggregation, extended model scope, and support for context-dependent component performance. Examples using the *deeco* (dynamic energy, emissions, and cost optimization) energy system modeling environment are given. Multi-agent simulation and high-resolution modeling have similar underlying architectures and can be combined to yield entity-oriented modeling. This new technique additionally supports decentralized decision-making, automatically captures interacting commercial and technical dynamics, and may be used to investigate structural evolution. A summary of national energy policy modeling strategies and a roadmap are provided.

1. Introduction

Many nations are seeking to improve the public interest performance of the systems which supply fuels and energy-services to industry, commerce, and households.[1] These systems are under continual change over a number of dimensions, including: disaggregated demand, operational practice, market status, physical capital, technological progress, technical standards, institutional context, and natural resource holdings. Governments can, through judi-

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[1] The term *energy* is favored throughout this paper, although, in most cases, the term *exergy* would be more technically accurate (Bejan et al., 1996).

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cious intervention, influence the evolution of the energy-services supply systems (ESSS) within their jurisdictions in order to address topical public interest deficits. Given the complexity of these systems, public energy policy formation needs to be underpinned by good data and robust numerical modeling. The question of how best to structure and apply energy policy models[2] is also an ever changing field, contingent on the policy issues of the day, advances in computer hardware, and developments in economics, engineering, sociology, mathematics, and computer science.

Priority public interest issues at this juncture are taken to include: financial cost reduction, climate protection, and depletable resource use displacement—together with local concerns such as competition failure, supply reliability, and various environmental and social impacts.

The past two decades have seen many changes to the institutional, technical, and social realms within which energy-services supply systems operate and evolve. Of particular interest is an evident shift in thinking in respect of technologies, resources, and architectures. The primary resource mix has continued to diversify and there is now genuine consideration of new renewables (including wind and biomass) and passive means of supply (including insulation and solar architecture). Conversely, nuclear power has, thus far, fallen well short of deployment expectations. But perhaps the most profound change has been the attention accorded to new forms of system organization—discussed variously under the headers of distributed energy technologies (DET), resources (DER), and solutions (DES).

The phrases DET, DER, and DES tend to place emphasis on the technologies involved, but the concept is as much an *architectural paradigm*—for which structural integration and operational coordination are as important as the stand-alone characteristics of the components themselves. This *component/system* view introduces new policy modeling challenges because the classical treatment of technology uptake focuses on the potentiality of specific technologies in relatively coarse circumstances. By contrast, distributed technologies tend to be sensitive to their actual deployment context—as defined by the adjoining infrastructure and unit commitment practices, the existing and likely future commercial settings, and the prevailing environmental and institutional circumstances. This often means that the system-oriented benefits of distributed technologies can only materialize where suitable integration, coordination, and benefit sharing mechanisms prevail.

From the *component perspective*, the term DET—as used here—covers a raft of interconnected small to medium-scale technologies, technical upgrades, and management strategies used for the supply of energy-services. Examples of DET include: renewable generation, local generation and cogeneration, dedicated biofuel cropping, component efficiency improvements, waste heat reclamation, passive point-of-service measures (including insulation retrofit), dispersed storage, modified unit commitment practice (including non-financial dispatch criteria), and user-domain flexibility (including elected demand deferral).

The numerical portrayal of distributed technologies is not easy. Nonetheless, public policy energy models need to adequately capture DET if they are to avoid technological discrimination and produce robust conclusions. The task of projecting the potential uptake of distributed technologies and identifying their likely public good contribution (for instance, toward carbon mitigation) is even more difficult.

This paper introduces two forms of model structure. The first, entitled *high-resolution* (HR) modeling, facilitates an even-handed assessment of both distributed and centralist technologies. This structure can then be combined with *multi-agent simulation* (MAS) to yield a second form, *entity-oriented* (EO) modeling. HR modeling is able to reflect technical behavior in the presence of one endogenized (model internal) decision-maker, whilst EO modeling is additionally able to capture multi-participant commercial behavior. HR modeling is, in effect, a subset of EO modeling and most comments relating to HR modeling apply equally to EO modeling.

The UNIX-based application *deeco* (Section 5) is cited as one example of a high-resolution modeling environment suitable for certain forms of national policy analysis.[3] Work has also begun on a new EO

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[2] On occasion it may be necessary to distinguish between a *modeling environment* and a *model instance*, otherwise the term *model* can be taken to cover both concepts.

[3] The *deeco* project website is hosted at: http://www.iet.tu-berlin.de/deeco

modeling environment called *xeona*. The purpose of this paper is to explore how best to represent DET in national policy models and to think about how the next generation of policy models might be crafted. And while the focus is on national policy support, much of this discussion is also applicable to municipal and remote systems.

Some matters relating to terminology conclude this introduction. Oxidizable compounds, electricity, and transported heat[4] are described as *fuels* when used to supply downstream processes (Bejan et al., 1996). The term *energy-services* refers to the provision of energy-related amenities specified using physical intensities,[5] such as indoor temperature. The term *component* normally refers to the physical entities (hardware) which form the network structure, whereas the term *technology* includes information-centric options (software in the broad sense) as well. The term *cost* is used in its financial context—other forms of cost not exposed in monetary terms are described as *impacts*. The term *national* also covers policy-harmonized groupings of countries, such as the EU.

2. Distributed energy technologies

Distributed energy technologies are difficult to accord a single concise definition. One approach is to provide screening criteria based on scale, placement, ownership, and operational authority. Another is to list representative examples, usually grouped by engineering design and product stream.

Both approaches tend to overlook important *information-centric* options, which might include: choice of unit commitment objective (minimized: short-run marginal cost (SRMC), CO_2-e (equivalent) emissions, or local air pollutants), modified use-of-storage strategies, administered multi-party cooperation, and rewarded end-user flexibility. Information-centric options can be highly worthwhile, as the following two electricity sector illustrations indicate. Reservoir and demand management practices within a hydro-dominated system can spell the difference between normal operation and crisis mode in times of low inflow. And customer flexibility can be an exploitable system resource through initiatives like the web-auctioned purchase of customer-elected demand deferral.

Similarly, *fuel-passive point-of-service* measures tend to be accorded less attention then their active counterparts. Fuel-passive measures include: insulation upgrade, solar architecture, and switchable transparent insulation (STI). STI is an intelligent passive solar technology suitable for retrofit (Lindenberger et al., 2004).

Fortunately, the ideas presented in this paper do not require a formal definition for DET, at least not as far as HR and EO model formulation is concerned. These model lineages are sufficiently general to cater for most types of system intervention—be they centralist, distributed, information-centric, fuel-passive, or some combination thereof. In fact, one of the merits of HR and EO modeling is their relative absence of technology bias. Conversely, the question of partiality becomes important when dealing with less-resolved and/or less-expansive modeling strategies.

Nonetheless, a working description of DET is required in order to direct policy-related discussion. This paper adopts a test-based approach. DET are defined as those system interventions—be they physical or informational—whose technical, commercial, and/or public interest performance is somewhat sensitive to *placement* and *operation*. So-called *centralist* technologies, on the other hand, tend not to be as susceptible. This interpretation considers both the technology and the host system, which makes it qualitatively different from the component attribute view discussed earlier.

The degree to which DET deployment might provoke a new structural paradigm for energy-services supply remains an open question. As might be expected, the clearest expressions of any such shift in paradigm are narrative rather than quantitative. One of the more ambitious accounts was published in *Wired Magazine* by Silberman (2001), while a more measured portrayal, also built around new information technologies, is provided by Siemens, Germany (Bitsch, 2001).

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[4] The term *transported heat* is taken as shorthand for *net-transfer of physical flow exergy*.

[5] The term *intensity* refers to quantities which do not scale with (Gibbsian) simple system or (standard model) market size. Examples include temperature, lux level, specific emissions factor, and, in the absence of scale effects, unit fuel cost.

The use of distributed technologies can be motivated for a number of reasons, whilst noting that situation-specific analysis is required to verify these attributes. From the *user* perspective, the use of DET may provide additional supply security, avoid or reduce interconnection and fuel charges, and perhaps yield installation-specific co-benefits ranging from improved health status to better product quality. From the *grid operator* perspective, the use of DET may defer infrastructure upgrades, including additional high-voltage transmission circuits, assist local energy-services supply security, and improve operational flexibility. From the *social* perspective, the uptake of DET may provide environmental and resource use benefits, help meet national emissions commitments, and contribute to local, national, and regional energy security.

Some of the drivers for DET have been reinforced by the adoption of network pricing methodologies, designed to signal the presence of network effects (Section 3). Such pricing schemes arose from sector liberalization. As an example, Outhred and Kaye (1996) describe the Australian implementation of wholesale electricity nodal pricing. Under these methodologies, (discretized) real-time price formation can be noticeably volatile, particularly where key market participants are able to capitalize on their zonal market power in times of system stress (Harvey and Hogan, 2000). Such volatility means that it may be necessary to model down to *market resolution* on both the topological (nodal) and temporal scales (or some limited aggregation thereof) in order to understand the economic benefits that DET might offer. This resolution is indicated because the commercial stimulus for both grid and user-domain DET solutions may well be driven at the margin by price exposure and perhaps also supply risk. Without sufficient resolution and scope, niche opportunities for DET will necessarily remain opaque to analysts, operators, and investors in all but the simplest of cases.

Distributed technologies often exhibit lower component efficiencies when compared with their large-scale counterparts—a characteristic sometimes given as a counter-argument. For instance, at full-load, a 400 MW_e gas-fired combined-cycle gas turbine (CCGT) generator set can realize generation efficiencies (based on LHV) of about 55%, whereas a modular 30 kW_e micro-turbine might yield about 22%. In both cases, exhaust temperatures are comparable. But although DET hardware may lose in terms of technical economies of *scale*, they often gain ground through *proximity* to demand. All network-supplied energy-services can be associated with a *marginal supply chain*—defined as the network routing which supplied the last one-unit increase in requirement (Morrison, 2000). Conversion and transport inefficiencies naturally compound as one moves upstream (Tsatsaronis, 1998), thereby disadvantaging topologically more distant plant. A related concept is that of *modularity*, whereby a number of units are connected in parallel, thereby enabling individual units to more often run at or near peak efficiency. Modularity is a strategy used by centralist technologies as well. In most cases, numerical assessment is required to determine which influences—scale *or* proximity *or* modularity—will yield the best overall performance. Moreover the debate about appropriate scale also tends to overlook the fact that the bulk of point-of-service equipment is both small in size and highly distributed—for example, private dwellings, which supply (amongst other things) thermal comfort, are highly numerous.

In general, DET require good *operational coordination*—as represented by an explicitly stated (and modeled) *unit commitment policy*. In the electricity sector, for instance, system coordination normally falls to the independent system (or grid) operator (ISO), with participating generators progressively surrendering authority in the run up to dispatch. The ISO normally assigns generation shares in accordance with a published unit commitment algorithm. In the case of nodal pricing, this is a linear program (LP) with convex supply bids and stepwise transmission losses (Sanabria and Dillon, 1998).

Operational coordination can be viewed as a DET resource in its own right. One study (Ramsel, 2002) shows that unit commitment policy modifications for a working 100 MW_e municipal cogeneration facility can yield commercially attractive CO_2-e reductions (Fig. 2, here). This kind of abatement may well qualify under the Kyoto Protocol Clean Development Mechanism (CDM) and similar.

Logical DET entities can be created in order to better interface with the rest of the system. One such notion is that of *virtual power plant* (VPP), formed through the agreed coordination of surplus onsite capacity across several firms for the purpose of presenting as a single unit to their local ISO. Although the idea has attracted industry attention, questions of benefit reallocation and coalition stability remain topics for research (Fichtner et al., 2004).

DET which rely on intermittent renewable sources, such as wind power, introduce further system management challenges. However the near future output (perhaps out 24 h) from such technologies can be well estimated using weather forecast information. Moreover intermittent renewables can be readily included in HR and EO modeling, due to the use of high-resolution time-series.

Operational coordination is only one half of the story, the other being that of *structural integration*. Engineering intuition supports the idea that DET components work best when arranged in some sensible combination. To take a simple example: a wind-driven stand-alone power system (SAPS) might consist of a wind turbine, battery bank, and perhaps some (implied) end-user flexibility—and will have been conceived as an integrated package. More complex schemes require HR and EO modeling in order to determine and—through scenario iteration—make best use of the interactions that arise between components. More generally, the notion of component integration can be extended to include information-centric responses.

The *cross-technology interactions* which emerge can be *counteractive* or *synergetic*, depending on the circumstances, as reported by Bruckner et al. (1997). The same phenomenon is discussed by Sundberg and Karlsson (2000). And Gong et al. (2002, p. 5) note that the "systematic approach" of MIND (Section 5) "will also detect vital interactions". In terms of public policy development, these interactions translate into non-independence of intervention—the public policy implications of which are discussed in Morrison and Bruckner (2002).

Policy modeling has traditionally been slanted toward the 'supply side' for a variety of reasons, including data availability. A better representation of grid and user-domain technologies and the use of systematic policy implementation are now surely overdue. Even so, as part of their energy analysis of the 20th century US economy, Ayres et al. (2003, pp. 249–250) conclude that "during the past century, the locus of technical progress has moved from [second law] conversion efficiency to end-use efficiency or service output per unit of work".

In common with cost/benefit analysis (CBA) and similar, HR and EO modeling can be used for both public policy analysis and private project appraisal. These two application areas differ in a number of important ways. When working within public policy, there needs to be a careful distinction drawn between the costs and benefits that accrue to individual and cooperating private entities *and* to the defined society at large. Private appraisal normally omits negative externalities, uses capital market-informed discount rates, and defines plant life as the point at which discounted cash flow (DCF) is planned to become net-positive. On the other hand, national policy formation includes social costs (or some estimate thereof), uses social policy-relevant (lower) discount rates, and defines plant life in terms of expected length of service. All in all, these two problem constructs are substantially different and should not be mixed (Gruber, 1991).

Carbon trading is not considered in this paper, but EO modeling can support carbon markets posited on partial economic equilibrium.

3. DET and network dynamics

This section sets the notion of DET within a systems context and, in particular, the unique characteristics of non-steady-state resource-transforming networks. The term *network dynamics* encompasses both network effects and network externalities.

The concept of DET can be generalized to exclude necessarily arbitrary references to scale, technology, role (base load, peaking), fuel type, and/or market realm (wholesale, retail, internal, out-of-market) as follows. An *extended definition* for DET comprises those component upgrades/additions (predominantly hardware), network protocol changes (predominantly software), and system obligation shifts (predominantly demand behavior change) which are designed, often in combination, to reduce the costs, impacts, and supply risks associated with energy-services supply and for which network effects and network externalities are significant.

Briefly, *network effects* are the characteristics which emerge as a result of the capacitated and dynamical nature of resource-transforming networks (adopting a topological and intertemporal viewpoint) *in association with* the system management regimes in place (taking an algorithmic perspective) (Outhred and Kaye, 1996; Morrison and Bruckner, 2002).[6] Moreover, system management can be administered or market-based or some mix of the two. And certain commercial practices, including constraint gaming, can also contribute to the development of network effects. The motivation for forming and extending networked systems arises from the presence of favorable network externalities. Briefly, *network externalities* are the benefits that accrue to participants from interconnection (Katz and Shapiro, 1985). The pricing of network effects and externalities is a complex topic and one not traversed here.

The term *network* is used in its mathematical sense and includes fuel supply obligations (be these primary or derived), fuel sourcing options (depletable and renewable), and the system management routines/solvers in place (often structured as least-cost). The portrayal of energy-services supply systems thus is quite natural in most cases. The benefits of interconnection—the network externalities—are largely self-evident, at least on a qualitative level. Similarly, the consequences—or network effects—of full or partial *network saturation* are also reasonably intuitive, although difficult to fully appreciate without modeling.

This extended definition for DET gives rise to the following important corollary. HR and EO modeling are indicated in cases where the system under investigation exhibits significant network dynamics—moreover, the granularity of these effects and externalities sets a *minimum bound* on the modeling resolution. This observation has parallels with Nyquist sampling, which similarly places a lower bound on the sampling frequency in signal processing.

4. National energy policy modeling

A number of modeling strategies have been used to construct national energy policy models. Five main approaches can be identified, deriving from, respectively, econometrics, general equilibrium economics, input–output analysis, mathematical programming, and system dynamics (Bunn and Larsen, 1997a). Efforts to combine these various approaches in order to overcome methodological limitations and increase model applicability have met with mixed success—in part because the assumptions and constructs behind each strand can be quite different and, in some cases, strongly incompatible. Multi-agent simulation is also under development but this technique has yet to be applied to working policy models. New modeling strategies will doubtless be developed in the future.

Useful national energy policy model overviews include: Kydes et al. (1995), Bruce et al. (1996), Bunn and Larsen (1997b), MIT Energy Laboratory (1997), Barker (1998), van Beck (1999), and Metz et al. (2001).

Some policy questions require long-term projections of the energy-services sector—in particular, questions associated with climate change and with future energy-services security. One application category, known in the literature as *long-term* modeling, seeks to project energy system characteristics over a span of decades. Such models were originally developed to examine issues of primary energy supply, but, more recently, long-term models have been revised to support climate-change-related energy policy formation—and the field duly re-titled as *energy–economy–environment* (E3) modeling.

Long-term energy policy models need to capture the coupled dynamics of economic activity and technological development/diffusion. With regard to *economic activity*, three distinct strategies are used. Standard optimal growth models which contain sector-specific production functions can be extended to include greater energy sector detail. Econometric macroeconomic models can likewise be extended. And technology-oriented intertemporal optimization models can be coupled with reduced-form equilibrium modules, such that both modules exchange quantity and price information until convergence is reached. Examples of the second and third strategies include

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[6] Some business studies researchers use the term *network effects* in the same way this paper defines *network externalities*. Also, *network effects* may be called *grid effects* within the electricity sector.

E3ME (Barker, 1998) and MARKAL-MACRO (Kypreos, 1996; Morris et al., 2002), respectively.

The question of representing *technical progress* in E3 analysis is more problematic. Long-term models need to generate, by way of endogenous discovery, reasonable information about the future costs, attributes, and deployment dynamics of known and anticipated energy-services supply options. The general issue is known as *induced technological change* (ITC) and is the subject of substantial research interest—see Weyant and Olavson (1999), Barreto (2001), Löschel (2002), and Nakićenović and Riahi (2002).

This inquiry is complicated by at least two substantive issues. First, the process of individual technology development and diffusion normally involves *positive returns to adoption* and is thereby prone to phenomena seen in nonlinear dynamics, including critical mass thresholds, path dependency, and undue sensitivity to boundary conditions and stochastic influences. The notions of network externalities and positive returns to adoption are closely related. And second, the question of *cross-technology interactions* arise, whereby the system-wide contribution from a mix of technologies is no longer the sum of their stand-alone contributions. Network effects and cross-technology interactions are similarly closely related. This second issue has received less research attention. E3 models in their present orientation use the approximation that fine-grain cross-technology interaction can be safely ignored. In contrast, early results from HR modeling suggest that these interactions can be highly significant (Bruckner et al., 1997).

Moreover, existing technology-centric network optimization-based E3 models have insufficient resolution to adequately capture most DET. These models typically rely on base and peak load demand profiles to compute primary annual source and system infrastructure capacities, respectively. And even though there is a trend for these models to disaggregate spatially (Kanudia and Loulou, 1999) and temporally (Remme et al., 2001), it is difficult to envisage existing models becoming strictly HR. This view is formed, in part, because the GAMS and AMPL languages–on which most such models are based–are not object-oriented (OO) and that the software complexity of generic HR and EO modeling environments probably necessitates OO programming.

The model types discussed in this section are designed to examine the linkages between the economy at large and the ESSS sector more specifically. These model types have traditionally been sorted into two camps: *top-down* (TD) and *bottom-up* (BU)—which can be taken as shorthand for economy-centric and technology-centric, respectively. More importantly, these two approaches generally yield very different policy advice regarding the potentials and net-costs associated with climate change-motivated interventions. The IPCC Third Assessment Report (Metz et al., 2001, p. 489) comments that “[Bruce et al. (1996)] concluded that the differences between [TD and BU model] results are rooted in a complex interplay among the differences in purpose, model structure, and input assumptions.” Moreover, many of the long-term models in current use are thought to be too conservative when representing technological change. If true, climate protection studies based on such recommendations may be unnecessarily skewed toward present-day inaction.

Three other model types deserve mention. Economic *input/output* modeling is widely used for short-run economic analysis, but has limited application in regard to DET policy formation. Policy studies using *system dynamics* techniques are occasionally published, although issues of validity in relation to DET interaction appear not to have received attention. One example concerning distributed systems prospects and built using VENSIM is by von Moers et al. (2002). Finally, *energy accounting* models, such as LEAP (Heaps, 2002), rely on disaggregated extrapolation to provide scenario analysis and are fundamentally incapable of capturing DET interaction effects.

Not only do governments need information from long-term projections regarding problems that have yet to materialize, they also need to enact policy measures which are intended to have more or less immediate effect. This latter function can be termed *policy implementation* and its overarching counterpart *policy formation*. HR and EO modeling have a particular niche in regard to *supporting* DET policy implementation.

5. High-resolution modeling

High-resolution (HR) modeling utilizes an intertemporal process/flow framework within which a network of components (plant) source, store, transport, and transform fuels and/or supply energy-services in response to demand. The question of which plant to commit in any given interval relies on a predefined combination of mathematical programming (typically linear or mixed-integer linear), optimization heuristics (including genetic solvers), and/or procedural (as opposed to declarative) rules. Temporal resolutions of 1 h are common and most models span one or more years. Outright fuel demand (including electricity) must be specified using complete load (demand) curves because *load duration* curves lack intertemporal information. Topological aggregation can be used to reduce the problem size where appropriate. Some HR models support plant efficiency, capacity, and cost/impact creation dependencies based on external conditions, operational attributes (including heat transport temperatures), and internal state information. This then allows HR models to represent (exergetic) losses in storage[7] and continuous processes with greater realism than would otherwise be possible.

Several high-resolution modeling initiatives have been reported, but most are intended for facilities design under variable operation (Bruckner et al., 2003). The MIND/MODEST combination from Linköping University, Sweden can support public policy, although the current focus is on industry usage (Gong et al., 2002). The MIND program is being rewritten in Java using OO techniques.

Object-oriented analysis and design is well suited to the coding of generic HR and EO modeling environments. The relatively direct mapping between real-world entities and program-domain elements under OO design provides confidence in terms of conceptual validity. Of equal importance, OO programming provides for development flexibility, hybrid model building, and software reuse (Jaeger et al., 1999).

deeco (dynamic energy, emissions, and cost optimization) is a high-resolution ESSS policy support and local energy systems modeling environment. The majority of development currently occurs at the Technical University of Berlin, Germany. For technical accounts in English, see Groscurth et al. (1995), Bruckner et al. (2003), and the project website.[3] For representative applications, see Bruckner et al. (1997), Lindenberger et al. (2000), Morrison and Bruckner (2002), and Lindenberger et al. (2004).

In terms of software engineering, *deeco* is fully object-oriented. At run-time, individual plant are constructed from their respective classes (called *technology modules* in the documentation) and then placed within a graph container. At each interval, routines traverse this graph and variously set key intensities heuristically, resolve input–output (generalized efficiency), capacity (in the sense of maximum throughput or inventory), and cost/impact creation equations, formulate the optimization problem, invoke and interrogate the solver, compute any remaining costs and impacts, and finally update plant state registers. In one sense, *deeco* can be seen as a sophisticated matrix and report generator interfaced to an optimization package. In another sense, *deeco* is an entity-based network simulation for which the optimization solver is a proxy for the prevailing use-of-system policy (Fig. 3). Technically, *deeco* classifies as *adaptive recursive dynamic optimization*. *deeco* is written in C++ and runs on Linux and UNIX systems which support SVR4/x86 binaries.

6. The case for high-resolution modeling

The merits of combining TD and BU models have been debated for some time (Metz et al., 2001). However, the need for more detail in bottom-up models has only recently attracted research attention. Detail, in this setting, includes four aspects: (1) higher *topological resolution*, (2) greater *temporal disaggregation*, (3) extended *model scope*, and (4) support for *context-dependent component performance*.

The case for applying HR modeling to public policy questions involving DET is given from three angles: general arguments, reported shortcoming, and by example. The general arguments suggest that HR modeling can better capture important features of

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[7] Use of term *efficiency* to describe intertemporal exergy loss is not universal. Instead, the concept of *input–output relationship* is used within the *deeco* literature, which then avoids any semantic problems.

systems containing DET than other methods. The reported shortcomings mostly derive from concern over *topological* and *temporal* resolution. And, in order to demonstrate the merits of *extended scope* and *context-dependency*, two numerical studies using *deeco* are provided (Section 7). First the general arguments.

Higher topological resolution refers to *network detail* but allows the use of component aggregation where appropriate. The term *topological* rather than spatial is used because the underlying model is founded on graph theory and not geometry—notwithstanding, most primary components have physical locations. Greater temporal disaggregation (perhaps hourly) is required to retain important *temporal cross-correlations* within time-series datasets. Extended model scope includes support for demand specification in terms of energy-service, so that *fuel-passive fulfillment* may be considered alongside fuel-based options without prejudice. Context-dependent performance typically requires the use of *influential intensities*, either as model (endogenous) parameters or (exogenous) variables. In this sense, performance covers *efficiency*, *capacity*, and *cost/impact creation*. Performance dependence can derive from external conditions (including weather, pricing, and environmental impact restrictions), process attributes set by neighboring plant (typically *flo* and *return* temperatures), and internal state information to account for inventory (including resource quality via intensities) and operational history.

Some examples of context-dependent performance are in order. The interval-specific *capacity* of a wind farm is a function of wind speed, suitably characterized. Similarly, the interval-specific capacity of a gas turbine generator set is significantly dependent on ambient air temperature–full-load output can drop by 20% as the compressor inlet temperature rises from 15 to 35 °C.[8] The interval-specific component *efficiencies* of plant transacting heat can be strongly dependent on the intensive state of the recirculating heat transport media which connects them—for instance, condensing boilers work best when the *return* temperature remains *below* the dew point of the exiting flue gas. But unlike environmental intensities, which are necessarily provided as historic or synthetic data, heat transport and storage media intensities may need to be determined endogenously.

The use of performance-influential intensities effectively addresses the issue of *energy quality* within energy models. Morrison (2000, pp. 65–67) defines generalized energy quality in relation to HR modeling. Note too that context-dependency is a strictly local concept—in contrast to the notion of *network effects* which can propagate over extended sections of the system, often downstream of any prevailing minimum cut.

As far as the authors are aware, the general use of thermodynamic intensities in detailed national energy models was first investigated by Kühner (1996). van Gool and Kümmel (1986) had earlier considered the potential for temperature-characterized heat reclaim within individual economies and Groscurth et al. (1989) implemented these ideas in the aggregated LEO (linear energy optimization) model.

To our knowledge, no established optimization-based national or local policy model operates at the level of resolution indicated above and/or with context-dependent component performance based on endogenously set intensities. In terms of temporal resolution, other models use, at best, selected load-sets to determine system capacity and sourcing requirements. Such estimates are often derived from load duration curves (as opposed to load curves), whose creation necessarily masks important inter- and intra-time-series correlations. For instance, MARKAL-Lite, a variant of MARKAL developed for local energy planning (LEP), defaults to a six-step load duration curve approximation (Haurie, 2001, p. 19). And the E3Net model from Stuttgart University, Germany does not support contiguous (unbroken) hourly intervals (AGFW, 2000a).

A number of non-optimizing *techno-economic* (TE) models have been developed with high levels of detail, including temporal resolutions well below 1 h. Most such models cover only the electricity sector and are primarily used for planning and design purposes. TE models have been applied to support energy policy measures by *displacement*, whereby new technologies are assessed in what might be reasonable circumstances and these results used to inform lower-resolution policy models. This strategy

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[8] Calculated using 2001 data for the ABB Alstrom Power 17 MW_e GT35C gas turbine generator set.

can be useful, but will lose validity where important cross-technology interactions remain undetected.

Several researchers have indicated a need to include greater technical and/or commercial detail in energy policy models and to increase the topological and temporal resolution correspondingly. Their observations and recommendations are outlined next.

AGFW: The Arbeitsgemeinschaft Fernwärme (Working Group for District Heat) pre-study (AGFW, 2000a) and main study (AGFW, 2000b) reports discuss the potential and merits of accelerated cogeneration uptake within Germany. The pre-study (pp. 525–559) argues for a new generation of policy models with greater topological and regional breakdown. Such a structure is motivated by the need to better represent cross-technology interactions. The pre-study uses E3Net and the main study (ongoing) has adopted TIMES (a MARKAL/EFOM hybrid) (Remme et al., 2001).

IEA: An IEA-sponsored study on advanced LEP (Jank, 2000, pp. 61–62) describes how MARKAL and the TE model MARTES sized cogeneration plant differently in the same circumstances. The discrepancy is partly explained by differences in annual load curve resolution—in this case, MARKAL relied on a 5-point approximation whereas MARTES processed the original high-resolution time-series.

EFOM: Grohnheit (1997, p. 115) discusses the limitations of the typical day profile approach to determine system capacities when modeling electricity sector expansion in the context of DET. These comments relate specifically to EFOM, but are applicable to BU models more generally. The typical profile approach also forces the use of typical values for other intensities (including ambient temperature) which may also obscure other important intertemporal correlations and related context-dependencies.

IKARUS: The German IKARUS (Instruments for Greenhouse Gases Reduction Strategies) project report (Markewitz et al., 1998) on cogeneration potentials concludes that current optimization-based BU models are unsuitable for DET and recommends a new generation of highly resolved simulation models be developed.

Risø: A study on CO_2-e abatement potentials by Risø National Laboratory, Denmark (UNEP, 1994, pp. 27–28) notes the prospect of adverse interactions between carbon abatement measures treated as independent. The study recommends that future assessments use techniques that can capture cross-technology counteractions, thereby producing "integrated" rather than "partial abatement [cost] curves".

Shared Analysis: The European Shared Analysis program report on cogeneration, renewables, and energy efficiency (Grohnheit, 1999, pp. 9–14) argues that the current European Commission-sponsored BU and TD models are inadequate for DET, particularly in liberalized environments. Rather, a much broader model framework is required, which supports the detailed representation of distribution networks and buildings and also agent behavior (which thereby implies EO modeling).

Nearly all of these observations derive from attempts to provide policy support for a diverse range of DET using existing models. Such comments should come as no surprise, given the earlier definition accorded DET (Section 3). One common thread is the need to develop modeling techniques which better utilize *resolved data*. In particular, the need to abandon spatially aggregated annual or seasonal average and peak values and instead adopt datasets which preserve important topological and temporal information.

However, simply increasing the resolution of policy-oriented energy models is not generally sufficient for policy investigations dealing with DET. Although the variability present in sourcing and demand can be incorporated thus, the issue of context-dependency remains problematic. HR modeling, in contrast, supports context-dependency—which also includes the influence of operational history. This means that the various performance coefficients are not supplied as input parameters, but are instead calculated as nonlinear functions of their dependencies. These calculations provide a tangible point of difference between HR modeling and established national modeling techniques albeit with improved resolution.

7. Numerical examples

This section presents two studies involving the same German municipality and built using *deeco* (Section 5). The fuel cell study demonstrates two points. First, an improvement in model fidelity when context-dependent rather than fixed component efficiencies are used. And second, the sensitivity of system-wide performance on the actual selection of controller set-points. The gas turbine study reveals a greenhouse gas mitigation resource quantifiable *only* through high-resolution modeling.

In both studies, the status quo system includes a central facility comprising a network of coal and gas-fired boilers, steam manifolds, and extraction-condensing steam turbine generator sets. This facility supplies district heat and power and can offset electricity imports by up to 100 MW_e. External electricity and gas purchase contracts are modeled using stepwise (banded) tariffs.

The fuel cell study (Heise, 2003) investigates a technology in pre-commercial form. Stationary gas-fired fuel cell installations are predicted to play a useful role in the supply of domestic heat and power. However, the prevailing context can have a strong influence on the overall efficiency, CO_2-e mitigation potential, and financial attractiveness of such installations. Policy models need to be able to capture such dependencies where these might be important. Fig. 1 shows the emissions reductions when 200 kW_e phosphoric acid fuel cells (PAFC) are added to existing short-range municipal district heat grids, with surplus power sold back to the local utility. Controller set-points also become important because, at full power, the heat delivered with a *return* temperature of 40 °C is more than double that for 70 °C (Uhrig, 1996).

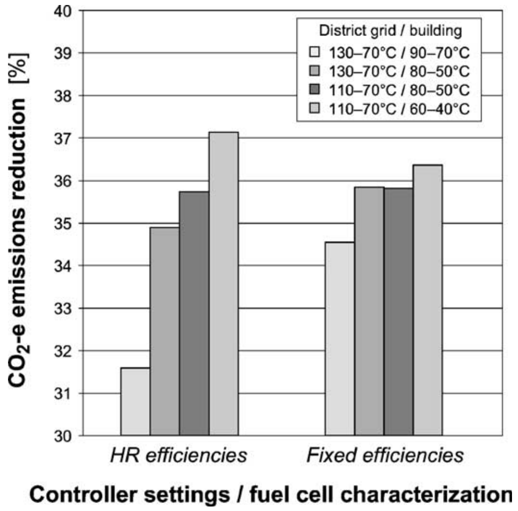

Fig. 1. System-wide CO_2-e mitigation performance versus four combinations of grid and building *flo* and *return* temperature settings *and* two fuel cell characterizations of differing sophistication. The same 200 kW_e phosphoric acid fuel cell (PAFC) is being modeled in all cases. The installation includes a condensing boiler in parallel.

In order to investigate the merits of context-dependent performance, this study tests two fuel cell characterizations of differing sophistication, each encapsulated within its own *deeco* technology module. The simpler method uses fixed heat and power conversion efficiencies, whereas the 'HR' method re-calculates these efficiencies based on prevailing heat transport temperatures. The characterization for the condensing boiler used to cover peak heating also relies on temperature-dependent conversion efficiencies. These transport temperatures and efficiencies are re-calculated for each hour. Fig. 1 indicates that the system-wide mitigation performance variation is 4 percentage points more pronounced for the HR method over a range of *flo* and *return* settings. The more sophisticated fuel cell representation is therefore indicated in this situation. Note too that controller set-points need to be selected with regard to system-wide performance and worst-case demand.

HR modeling and established national modeling techniques also differ in terms of *extended scope*. Extended scope indicates that fuel-passive technologies, revised network management, and end-user responsiveness can be included and investigated. This next study considers, amongst other things, alternative supervisory control objectives.

The gas turbine study (Ramsel, 2002) examines upgrades to the central cogeneration facility, namely the replacement of a gas boiler by either: (A) a single 43 MW_e gas turbine generator set with supplementary firing to provide up to 120 MW_{th} of steam at 75 bar for use in turbines, (B) *as per* A but with two smaller gas turbine gensets instead, and (C) *as per* B but providing up to 60 MW_{th} of steam at 3.5 bar for direct district heating only. Financial analysis includes support from the German *feed-in* law for cogenerated electricity (effective 2002). Fig. 2 shows A is the best option in financial terms, but is slightly outperformed by B regarding abatement. A and B perform well because the gas turbine(s) are configured to create an efficient combined cycle system. In contrast, C is not a combined cycle

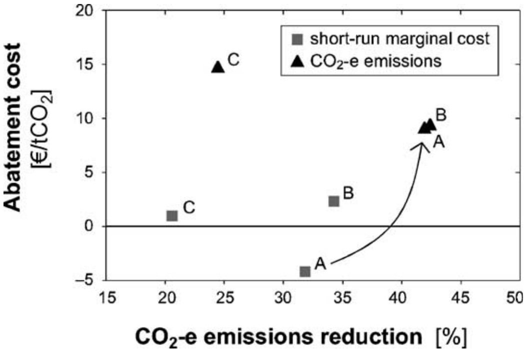

Fig. 2. CO$_2$-e abatement through revised unit commitment policy objective for central facility upgrade options A–C. *Source*: Ramsel (2002).

arrangement and therefore performs less well, as might be expected. For all options, the best outcomes result when operating in maximum cogeneration mode. Fig. 2 also shows the effect of simply changing the site-wide unit commitment policy *objective* from minimized short run marginal cost (SRMC) to minimized CO$_2$-e release for each option (which, in the SRMC mode, had already produced substantial cuts). Given option A is selected, this operational revision offers a further 10 percentage points of abatement and would become attractive at carbon prices above € 15/tCO2 (or 55/tC).

In both studies, the underlying system-wide emissions reductions were substantial, typically in excess of 30%. In the gas turbine case, a change in system operation yielded a further 10 percentage points. And in the fuel cell case (HR method), a poor choice of controller settings could undermine potential reductions by as much as 5 percentage points. These are significant gains and losses, and are comparable to the −5.2% aggregate target set down for the first Kyoto Protocol commitment period 2008–2012.

Both examples lend support for the view that policy models with less resolution and fixed component efficiencies may fail to both *capture* and *capitalize on* the operational flexibility contained within modern energy systems. Operational flexibility, as characterized by controllable degrees of freedom, is particularly important because individual sub-systems are increasingly being required to operate under conditions of greater volatility.

8. Entity-oriented modeling

HR modeling can capture fine-grain technology interactions but it cannot endogenize the commercial processes that arise between multiple participants. For that, entity-oriented modeling is required.

A key rationale for ESSS sector liberalization was to facilitate decentralized decision-making and thus improve allocative economic efficiency. As a result, sector participants now typically face more options and increased decision complexity. They may also have greater risk exposure, depending on their positioning along the purchase chain, the contracts and hedging instruments they hold, and whether or not they participate in primary markets.

National policy models will need to adapt to this new context, commensurate with their policy role and underlying formulation. One response has been to add multi-agent simulation (MAS) to existing electricity sector TE models. Under MAS, autonomous intelligent actors are introduced into the model domain and then allowed to interact in accordance with their preprogrammed characterizations. The actors normally have defined motivations, limited jurisdiction, and full cognizance of public domain information. The actors may also be able to learn and adapt, utilize foresight, and form multi-party coalitions. The actors can also be provided with decision-analysis tools, either dedicated, recursive (the underlying simulation is recalled), or external.

Model instances are then simply triggered and left to evolve as circumstances dictate. Some researchers describe these environments as *e-laboratories*. The use of evolutionary models is not without criticism regarding predictive validity—however the method is well suited to the exploration of issues of path morphology and regime stability.

Fig. 3 shows, in broad structural terms, how HR modeling is being modified to support actor entities. Each *entity category* (actor, block, etc.) is progressively specialized using extensible object-oriented class hierarchies. Each interconnected entity *instance* is held in a dedicated *graph container* which represents the appropriate *association* (actor relationship, component connection, etc.). The coordination layer can contain both strictly administered and spot market-based operational coordination mechanisms. This development draws on: computational econom-

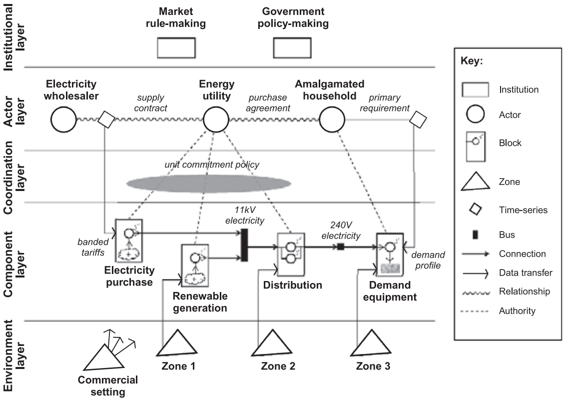

Fig. 3. A five-layer entity-oriented model structure which builds on the existing high-resolution modeling environment *deeco*. The model instance depicted is deliberately simple so that the underlying arrangement can be emphasized.

ics (Tesfatsion, 2002), multi-agent simulation (Weiss, 1999), multi-actor electricity sector models (Weinhardt et al., 2000; Bower et al., 2001; North et al., 2002), coalition formation (Shehory and Kraus, 1993), and game theory (Yeung et al., 1999).

9. A national energy policy modeling roadmap

This section describes how existing policy modeling lineages might adapt in response to new policy challenges and advances in computing. Fig. 4 depicts one possible roadmap. Although clearly simplistic, roadmaps can provide a useful framework for considering future modeling strategies. Because the focus of this paper is on disaggregated modeling, the formation of an *entity-oriented* (EO) modeling lineage is of most interest here. Conversely, the parallel question of how current bottom-up and top-down modeling strategies might merge to form a *long-range* (LR) modeling lineage is not traversed in any detail.

As indicated, *techno-economic* modelers are beginning to experiment with multi-agent simulation. This is, in part, because the conventional approximations of competitive equilibrium and standard model rationality appear difficult to sustain in the context of liberalized grid-mediated markets. These assumptions are being replaced with concepts like zonal market power (Harvey and Hogan, 2000), critical mass effects (Witt, 1997), and bounded rationality (Conlisk, 1996). Moreover, electricity market design in relation to complex ESSS has proved difficult to get right, hence an interest in market-specific multi-agent simulation (Bower et al., 2001).

The traditional role of *bottom-up* models—that of national capacity planning—is loosing relevance as sector liberalization transfers capital investment decisions from government to privately motivated actors. In addition, existing BU models are poor at representing DET for reasons discussed earlier. It is therefore difficult to see this modeling lineage persisting without substantial revision, given both market liberalization and an increasing public policy interest in DET.

The next modeling lineage comprises *top-down* models. These models are now widely used to investigate the effectiveness and the fiscal and welfare implications of energy sector policy interventions aimed at limiting climate damage. The usefulness of TD models is predicated on their ability to represent intrinsic sectoral development, both economic and technical. To date, TD models have not been able to capture technology evolution in a compelling manner. Hence, part of the motivation for introducing BU structure into TD models is to help address this problem. This initiative is materially different from that adopted by existing

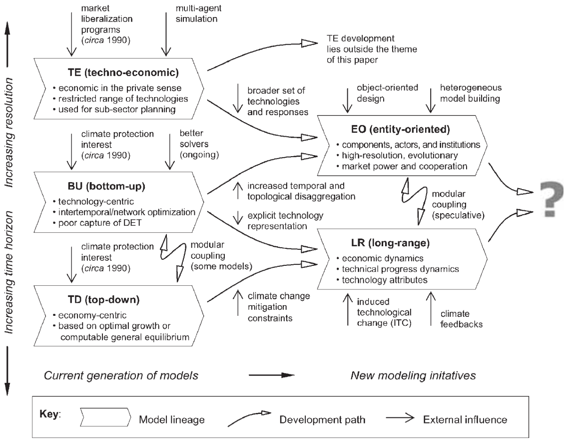

Fig. 4. A possible roadmap for the next generation of national energy-services public policy models. The *current generation* notation broadly aligns with IPCC (Intergovernmental Panel on Climate Change) usage, whilst the *new initiatives* notation is speculative. The roadmap does not include input/out and systems dynamics modeling lineages for reasons of simplicity.

coupled TD/BU models which use reduced-form macroeconomic modules to drive base BU models. TD modelers have already commenced work on the next generation of TD/BU models—labeled as *long-range* (LR) models for the purposes of Fig. 4—in an attempt to integrate the dynamics of technical progress. These new models aim to better capture technical development and technology diffusion, in order to provide support for (or reject) targeted policy assistance for selected technologies. The resulting LR models will doubtless still have difficulty capturing DET market uptake, technology interactions, and/or bundled policy measures due to their limited resolution and related issues.

10. Discussion

This paper presented two modeling strategies, both aimed at representing *distributed energy technologies* (DET) in policy evaluation models. The first, *high-resolution* (HR) modeling, is designed to capture the technical interactions and supervisory control practices which exist in complex volatile *energy-services supply systems* (ESSS). And the second, *entity-oriented* (EO) modeling, builds on HR modeling by adding agents and markets in order to capture the commercial interactions which arise when multiple decision-makers are present. Both modeling strategies are at an early stage of development, although HR modeling is the more advanced.

The types of entity supported by EO modeling include: local environmental and commercial circumstances, engineering plant and end-use facilities, unit commitment protocols and objectives, commercial and domestic actors, their energy-services and/or fuel demands, grid-mediated markets, incentive-based and mandatory public policy measures, and overarching socio-technical processes including induced cost decrease. The entity descriptions themselves can be quite sophisticated, thereby injecting a level of thermodynamic, economic, and behavioral realism not necessarily found in other modeling strategies. The model structure itself imposes relatively few limitations on technology characterization and allows energy-passive measures, such as uprated insulation and solar architecture, to be included. It also supports the use of temperature as a process variable, which can be important when investigating the potentiality of technologies like cogeneration, thermal storage, and heat reclaim.

The principal argument in favor of the above two modeling strategies involves the relative influence of *network dynamics* in relation to the other dynamics present in the system under consideration. These other dynamics include investment driven system evolution and any associated long-term causalities extant in reality. Such interactions often incorporate feedback and similar closed-loop mechanisms and may be identified directly and/or inferred from observed data. The term *network dynamics* describes the interplay of network effects and network externalities. Network effects are those effects which arise from (1) the capacitated nature of networked systems, (2) the temporal volatility present in sourcing options, demand requirements, exogenous pricing, and ambient conditions, (3) the influence of context on plant performance, covering efficiency, capacity, and cost/impact creation, and (4) the various operational protocols which react to and govern the ever changing state of the system. Network externalities are the net benefits which accrue from network membership and hence drive participant recruitment and retention. Network dynamics usually operate over shorter time-frames than other dynamics and tend to be more strongly influenced by the prevailing architecture and circumstances. Hence HR and EO modeling are indicated where network dynamics rate strongly.

Conversely, DET are identified in this paper using a test-based definition. DET are those existing or proposed system changes for which network effects and network externalities are significant. This approach automatically takes into account both the technology itself and the host system. Moreover, the types of effects and externalities that might emerge provide bounds on modeling resolution and scope. This definition is more encompassing than that normally found in the literature, and includes, for instance, strictly informational responses, such as revised network management and rewarded end-user responsiveness.

Two lines of evidence were presented concerning the need for HR and EO modeling with respect to DET policy. The first involves the observation that network dynamics are clearly present in most situations, with nodal price volatility in times of system stress providing one such manifestation. And the second involves the results from completed numerical studies whereby context-dependent performance and extended scope proved significant in terms of public interest outcomes. Notwithstanding, the specific justification for using HR and EO modeling rests with the particulars of each situation.

This is not to suggest that network dynamics need be fully reflected in long-range policy models. Nor that HR and EO models cannot embed other dynamics. But rather that the evaluation of public policy measures pertaining to DET, be they incentive-based or mandatory, provides a natural role for HR and EO modeling.

Being able to replicate the network dynamics associated with DET represents a useful contribution. But capturing the uptake dynamics of DET introduces further challenges. How best to anticipate, or at least understand, energy-services supply systems development trajectories in light of DET uptake represents a major theme of this paper. Two relatively polarized strategies seem to be in evidence. The first strategy is to better reflect technology interactions and technical progress within established economy-centric models—a research agenda which falls under the header of *induced technological change* (ITC). And the second strategy, advocated in this paper, is to use EO modeling in an evolutionary context, whereby key entities are placed in a proxy system and left to evolve in a manner consistent with the scope provided. Evolutionary-based EO modeling will doubtless yield less definitive results than conventional ITC modeling, but these results are more likely to reflect the uncertainties present in reality. Furthermore, it seems reasonable to speculate that the prospects which accrue to various DET are influenced by technology and commercial clustering effects, which may, in turn, result in detail-sensitive (or butterfly effect) uptake.

But whilst HR and EO modeling are potentially suited to the analysis of on-the-ground policy measures, the technique is not appropriate for setting overarching policy objectives. This latter task falls currently within the realm of integrated assessment climate protection models and economy-centric energy policy models—each of which span decades. Notwithstanding, these long haul model lineages are also in need of better information about likely DET uptake and technology diffusion in general. The relationship between these various model types could be viewed as symbiotic at this juncture—symbiotic in the sense that the interpretations from one modeling initiative can inform the strategies and tactics used in another. The ultimate goal, perhaps some years in the making, would be to combine these various strands into a single integrated assessment package in which all the various interrelated software components reside within the one logical model domain.

More immediately though, the salient issue for national energy policy analysts is whether they possess methods which naturally place DET options on an equal footing with centralist options. Or whether a new generation of HR and EO models will be required for this purpose.

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