High-resolution modeling of distributed energy resources using *deeco* : adverse interactions and potential policy conflicts [1]

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Abstract

Governments are currently introducing measures to stimulate the uptake of certain distributed resources (DR) within the energy sector as part of their domestic climate protection programs. The effectiveness of these initiatives may be undermined by network-mediated interactions between the DR themselves. This paper identifies several types of interaction using the high-resolution modeling environment *deeco* (*d*ynamic *e*nergy, *e*missions, and *c*ost *o*ptimization) and presents these as emergent systems properties. It also provides a broader definition for DR than is normal for public policy analysis and discusses extensions to *deeco* which would allow network-based price discovery protocols to be supported.

1. Introduction

Many governments see merit in improving energy productivity, increasing primary supply diversity, and reducing energy-related CO_2-e (equivalent) emissions. For instance, Germany has recently brought in or strengthened public policy measures covering: (1) price and dispatch security for renewable electricity (feed-in law), (2) loan programs for building upgrades, (3) performance-based efficiency standards for new buildings, and (4) stimulus for cogeneration modernization and deployment. Providing analytical support for public policy formation in these and related areas raises a number of conceptual challenges. Given the present state of knowledge, robust analysis requires the application of several methods, each of which needs to complement the decision information provided by the others.

The focus here is on a particular form of exergy-services supply system (ESSS) modeling — one which places optimization functionality at the core, offers relatively high temporal and structural resolution, and sets key thermodynamic intensities internally (for example, heat transfer media temperatures). Detailed engineering simulations are replaced with reduced-form process/flow descriptions and system control protocols are substituted by unit commitment policies based on minimum cost flow routing. In terms of temporal resolution, the default time-interval is one hour. This form of modeling provides a more abstracted view of ESSS than would normally be the case with *engineering simulation* (using GateCycle, for instance) and greater structural detail when compared with traditional *optimization-based policy* modeling (under MARKAL, for example). The approach given therefore offers a bridge between these two established areas.

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Conversely, the temporal scope is short when compared with infrastructure turnover. A modeling horizon of one year is typical, sufficient to capture seasonal change but not generic economic and technical progress. This restricted span results from the fact that the system context — necessarily fine-grained — cannot readily be subject to closed-loop evolution. Hence, the method described is not applicable to analysis spanning years or decades, as this requires the dynamics of economic activity, technical innovation, and technology deployment to be represented — as is sought by *sector-specific macroeconomic* modeling (for instance, MARKAL–MACRO and PRISE [1]).

The form of modeling under consideration provides for extended structural scope by allowing system purpose to be specified in terms of exergy-service provision rather than *fuel* supply. It also allows speculative technologies to be evaluated *in situ* without requiring detailed characterizations. And in addition, there is no need to restrict attention to the realm of formal energy markets.[2]

This paper presents the UNIX application *deeco* — *d*ynamic *e*nergy, *e*missions, and *c*ost *o*ptimization.[3] *deeco* is a generalized ESSS modeling environment which supports high temporal and topological (structural) resolution, extended system scope (particularly in the end-use domain), and system management objectives other than least monetary cost [2,3,4].

deeco is classified as a *high-resolution integration* model — differentiated by the fact that operational variability is included as part of the system synthesis problem. Other energy system modeling initiatives which also qualify, at least in some respects, include: PRODESign [5] and work at Surrey [6] and Osaka [7] Universities.

In this paper, a given ESSS is interpreted as a patchwork of transacting networks interconnected by *gateways*. An individual network need not be contiguous and a network gateway need not be permanent. Networks that remain physically disjoint may still exert commercial influence if viable gateways can be envisaged. The extent of an individual network is defined by the presence of an identifiable *unit commitment procedure* (UCP) which controls unit commitment on that particular section of the system — in accordance with some nominated minimization objective. As an example, a particular UCP could mirror the electricity dispatch algorithms that an independent system operator (ISO) might apply. A UCP will need to contain use-of-storage policy if storage facilities are present — this policy may be non-anticipatory or forward-looking. In terms of model building, a given UCP may proxy a single site operator or the collective actions of a group of site operators. In principle, multiple UCP can be organized in flat or nested form, although the numerical details (decomposition) remain under investigation.

The ESSS itself is defined in terms of *exergy-services* provision. An exergy-service is necessarily specified using one or more physical intensities — for example: temperature, illuminance, material concentration, pressure, and velocity. Some indication of scale is also normally required or implied — for instance: floor area. The term *fuel* (set in italics) is given an extended meaning and includes work and heat transport under conditions of demand. Moreover, the concept can be further generalized to cover *emissions permits* and related forms of impact entitlement. The term *network* is used in its mathematical sense and naturally includes *fuel* supply and demand information — duly specified by equality and derived from knowledge about sourcing opportunities and supply obligations as necessary. The term *state* can include both physical and socioeconomic dimensionalities.

For the purposes of this paper, *distributed resources* (DR) comprise the set of all feasible exergy-services supply interventions which lie outside the wholesale market domain. DR interventions need not be restricted to hardware — a change of UCP management objective would conform [8]. DR interventions need not involve opportunity-costed *fuels* — for instance, measures to promote passive solar architecture would also be covered [9].

[2] The term *energy* is employed in cases where its usage is prevalent, otherwise the term *exergy* is preferred.
[3] The *deeco* project website is located at: `www.iet.tu-berlin.de/deeco`.

deeco can be used equally to support public energy policy formation and sustainability-motivated engineering design. The difference is primarily one of referred influence — governments usually favor incentives over compulsion, whereas owners can implement their decisions directly. In either case, the sought response is termed an *intervention*. *deeco* has been used to investigate local energy planning (LEP) problems [8,10,11] and to support retrofit [9] and new build [12] scheme design. *deeco* is currently being modified to enable national energy policy analyses based on *point-in-time* integrated assessment. *deeco* can also be employed for additionality appraisal under the Kyoto Protocol Clean Development Mechanism (CDM) and Joint Implementation (JI), but editorial limitations preclude further discussion. *deeco* accounts for both *fuel* flows and CO_2-e, SO_2, NO_x, and PM_{10} emissions and thereby falls under the header of *energy–emissions* modeling (EEM).

A number of public agencies see advantage in promoting the uptake of DR but are hampered by the analytical techniques available. *Mid-to-long-range* national policy models are of limited value because they lack the resolution and scope to portray DR satisfactorily [13]. High-resolution integration modeling is clearly superior in this regard, but does not support endogenous economic and technical evolution. Both approaches therefore provide complementary information and policy analysts should use their collective experience to generate appropriate policy recommendations.

This paper presents results from two numerical studies involving real and hypothetical investment options for a German municipal energy utility. These results will be discussed in relation to certain emergent phenomena — phenomena which have particular relevance for DR policy formation.

deeco does not currently contain price discovery and price elasticity mechanisms. A *nodal pricing* module based on the New Zealand wholesale electricity market auction process is duly proposed. This module is *not* predicated on general equilibrium but does require high-resolution bid and electricity network status information.

The various physical and conceptual entities which make up a *deeco* model may be mapped to agents who, in turn, can respond to the specific incentives they face. This observation raises the prospect of using *deeco* (or some successor program) as an ESSS engine on which to undertake agent-based modeling. The topic of commercially-motivated cooperation is particularly relevant for DR, given the fact that substantial benefits can accrue, that many key institutions and entitlements are now private or likely to become so, and that dispersed control protocols cannot be sensibly developed without some form of higher level collaboration policy in place.

2. Technical description of *deeco*

In mathematical terms, *deeco* combines discrete dynamical systems simulation with flow network optimization, both of which interact as the overall system evolves through a series of discrete time-steps [2,3,4]. Figure 1 indicates this general arrangement. Individual plant populate the network and are provided with interval-average information concerning supply obligations (for exergy-service and/or *fuel*), surrounding network status (if interconnected), and the prevailing physical and socioeconomic context. Gateway plant provide single point descriptions of neighboring networks. Exergy destruction — necessarily associated with intensive state change — can only occur within plant and is based on either level of activity or passage of time.

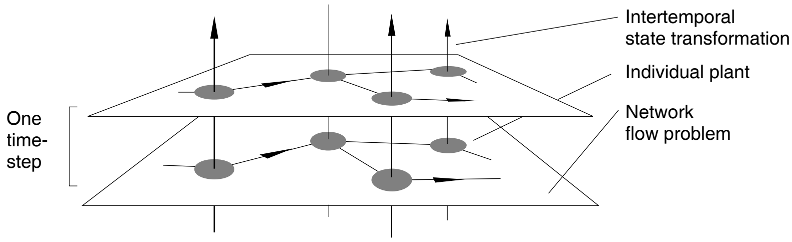

Figure 1: deeco as a sequence of interacting step-specific flow networks.

The optimization routine and nominated management objective, together with any prescribed rules, form the UCP. In the straightforward case, network flow-rates comprise the decision variables and one of the following flow-dependent minimization objectives is selected: CO_2-e, SO_2, NO_x, or PM_{10} emissions, depletable *fuel* use, or variable financial cost. This last category yields the network-wide short-run marginal cost (SRMC). The discrete dynamical systems simulation means that plant state transformation can be modeled, thereby allowing intra-step state dynamics to be represented. The presence of intertemporal exergy destruction in the form of storage depreciation means that state transformation and flow optimization must be prosecuted separately — and such that the nominal time-interval may need adaptive subdivision until convergence is reached. Closing inventories typically need to be honored. Technically, *deeco* classifies as *adaptive dynamic recursive optimization*.

deeco is implemented using object-oriented techniques. Each category of plant is granted its own class definition and plant instances are contained within a network object (graph container). For each time-step, traversal algorithms update the internal state of each plant instance, determine certain flow connection intensities, generate a step-specific configuration matrix and supply/demand vector, and pass this information to the UCP. The UCP is assigned the authority to set flow-rates — be they within or between plant instances. At present, the UCP calls a linear programming (LP) solver but this is currently being upgraded to mixed integer. The object-oriented structure also facilitates a well-organized data interface.

deeco is normally used comparatively, which means that promising scenarios are evaluated against some estimate of business-as-usual *by difference*. All supported costs are reported in annualized fixed and interval-average variable form, as appropriate, for subsequent aggregation and decision-support. However, only the UCP objective will have been minimized. From the viewpoint of *deeco*, integration benefits accrue to the network as a whole — some problems, including agent-based modeling, may require a subsequent reapportionment of operational costs and integration benefits.

3. Operational variability and interdependency

One issue that sets high-resolution integration modeling apart from established ESSS policy support and engineering design methods is the role that operational variability and cross-correlation plays in model formulation. The issue is one of increasing importance because ESSS plant are being required to operate in significantly more volatile contexts (be it *fuel* and off-take price, supply obligation, or planned outage policy) and renewable and passive technologies, in particular, are sensitive to environmental state (including ambient temperature, solar insolation, and wind speed).

Established energy system design strategies proceed by identifying a single steady-state operational regime based on maximum non-abnormal duty — the nominal *design point*. This context is used to propose and select (synthesize) and then specify (design) suitable hardware. After completion, software design commences in the form of *off-design* operational compromise under conditions of variability [14]. Public policy optimization models do not normally address operational variability to any great degree. At best, some models factor in variability using a small set of daily load profiles — for instance: week/weekend × summer/winter — deemed representative and necessarily treated as temporally independent.

deeco, in contrast, factors in interdependency-intact operational variability at the system synthesis stage. The system management policy — a software design issue in broad terms — is set before hardware synthesis takes place. If used for policy formation purposes, the method ends after hardware synthesis, otherwise plant detailing and analysis can continue using established engineering methods. Figure 2 summarizes the two approaches.

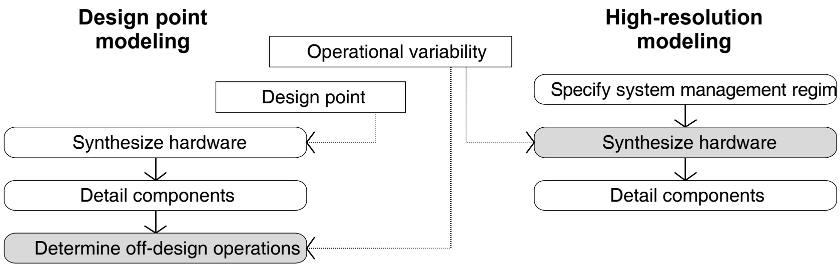

Figure 2: The role of operational variability in the design process — conventional and high-resolution modeling strategies differ in terms of the point of inclusion. The act of design is shown as single pass for the sake of simplicity.

In most circumstances, ESSS obligations are best specified in terms of exergy-service rather than *fuel* supply — for instance, indoor temperature *versus* heat demand. Supply obligations given as intensities naturally exhibit less variability and cross-dependence and this, together with the resultant increase in system scope, should enable scenarios with greater operational latitude (accessible state space) and better cost performance to be proposed. Finally, any decision to use operational time-series (such as, ambient temperature and heat demand) which fail to provide sufficient temporal resolution and/or maintain important cross-correlations should not be taken lightly.

4. Network effects, emergent phenomena, and integration deficits

The following network-level traits have been observed after applying *deeco* to local energy planning and single owner scheme design problems: (1) *counteraction* and *synergy* effects between multiple outwardly beneficial interventions, (2) economic and technical *lock-out* effects under sequential myopic decision-making, (3) *trade-off gains* through management policy revision, (4) improved *operational resilience* with increased system diversity, and (5) the identification of *system integration* as a valuable resource in its own right.

Such effects require certain preconditions: a level of underlying system complexity including some degree of operational variability. The classification of phenomena given is tentative and a more robust assessment would require certain network metrics to be defined and quantified — for instance, system diversity.

The two reported studies involve the same German municipal energy utility which supplies around 2200 TJ of electricity and 1200 TJ of district heat *per* annum. The utility can: (1) import wholesale electricity and gas from abutting transmission networks using consumption-history dependant tariffs, (2) run existing multi-fuel boilers and extraction-condensing steam turbines in various heat and power configurations, and/or (3) invest in new gas turbine cogeneration plant, thereby displacing electricity purchases and normally increasing gas usage. Electricity export does not occur in practice and was not modeled. Both studies sought to identify cost-effective CO_2 mitigation — this being the trade-off goal. And both used hourly data spanning one year.

Counteraction and synergy between multiple interventions. Counteraction occurs when presumed beneficial interventions give sub-additive results when combined — as interpreted in terms of the trade-off goal. Super-additive effects may also be observed under unusual circumstances. In the first study, Bruhn [11] added (Enron TS 1.5s) 1.5 MW wind turbines in 18 unit blocks in combination with storage-assisted solar thermal systems and/or gas-fueled reciprocating-engine cogeneration. Each so-called turbine block TB is nominally able to meet about 10% of average electricity demand. All scenarios include the use of peak-load condensing boiler CB — hence repeated mention of CB is avoided for simplicity. Figure 3 shows the technologies considered (the superstructure). Figure 4 displays the results on a trade-off diagram. A number of CO_2-e context counteraction effects are evident. The solitary addition of large solar LS and medium cogeneration MC give savings of 30% and 35% respectively, yet together these yield 44% — some 21%-points short of their simple summation. Previous work which employed a variant of this model found that such counteraction effects are more pronounced when building insulation is also upgraded [10]. Figure 4 illustrates more complex interactions arising from the staged introduction of TB. The TB trajectory (rising curve) for medium cogeneration MC shows rapidly diminishing returns to emissions reduction to the point where targets beyond 50% cannot be realized. The addition of small solar SS undercuts the role of cogeneration for heat supply and enables TB increments to contribute more and for longer to electricity supply. Medium solar MS augments this effect by providing for limited intertemporal buffering. Large solar LS, which supports cross-season transfers, further strengthens the intertemporal tie between solar and wind and allows targets as high as 65% to be reached. Broadly, these examples show how combinations of technologies may — depending on circumstances and the selected trade-off goal — work with or against one other.

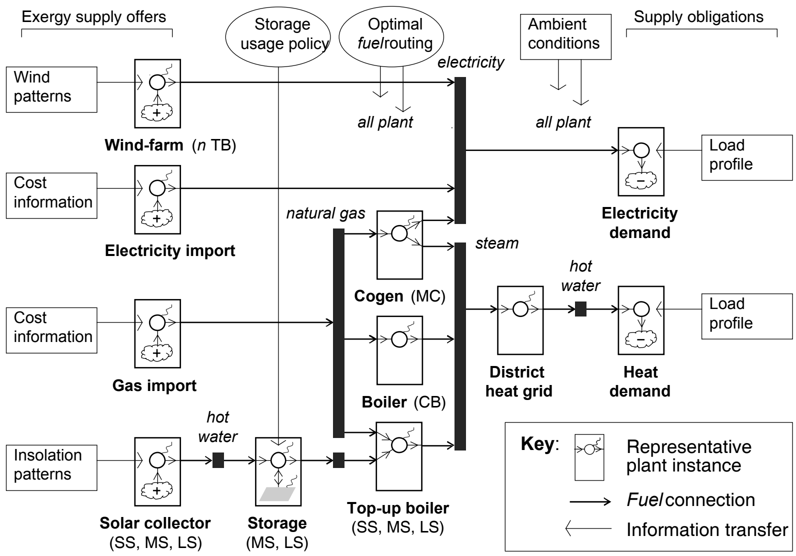

Figure 3: The superstructure for the incremental wind turbine study.

Lock-out effects under sequential decision-making. Sequential decision-making is, in essence, a form of multiple intervention distributed over time — the central issue being whether potential upgrade paths are evaluated in concert (and re-evaluated as decisions are taken) or whether each decision is made without reference to some long-term aim. Figure 4 demonstrates this effect. If reductions of 53% and 55% are required, then scenarios X and Y provide the respective least cost solutions. However scenario Y is not incrementally accessible from scenario X — a phenomenon known as *path-dependency*. If the ability to achieve a target of 60% at some future time is desired, then an investment path which includes locally underperforming scenario Z may be prudent. Given prior non-common interventions are to be retained (which is normally sensible), path switching will necessitate further analysis.

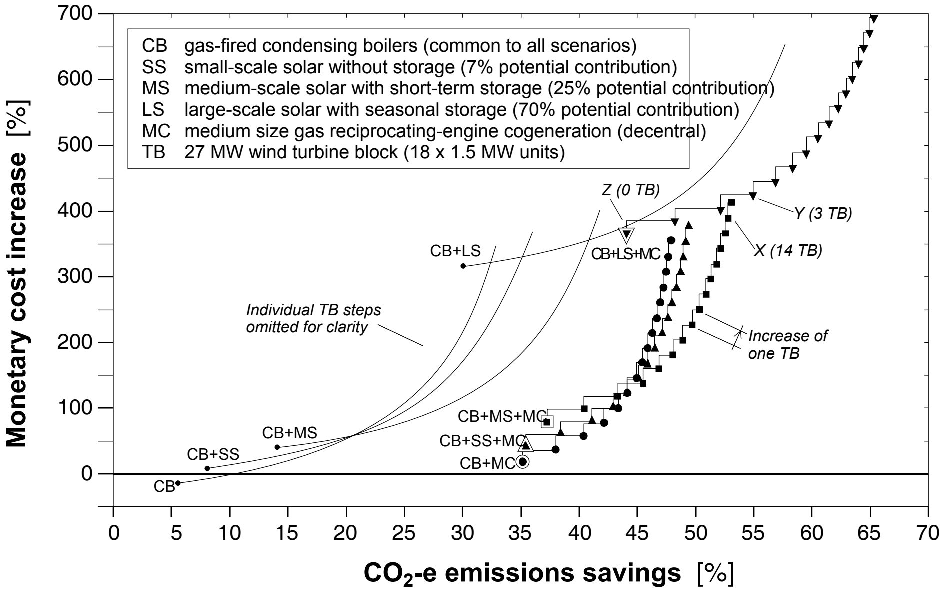

Figure 4: Counteraction and lock-out effects associated with the progressive addition of wind turbines in 27 MW blocks in combination with other base-line interventions.

Trade-off gains through revised unit commitment. In the second study, Ramsel [8] examined capacity expansion options for the central cogeneration facility run by the utility. A new shut-down mode heuristic was developed so that plant found to operate with poor average efficiency could be expressly disabled for that interval. And support for stepwise-increasing (banded) tariff structures was implemented to better reflect wholesale contracts. Three scenarios are evaluated: (A) a single 43 MW gas turbine and heat recovery steam generator (HRSG) supplying the existing extraction-condensing steam turbines, (B) two 24 MW gas turbines in the same role, and (C) two 24 MW gas turbines supplying the district heat grid directly. Additional HRSG firing is permitted. Current investment is treated as fully sunk, whilst proposed capital expenditure is annualized and included. The German cogeneration electricity feed-in law, effective from 2002, is taken into account. Figure 5 shows options A–C operated under conditions of minimum SRMC and minimum CO_2-e emissions. Option C yields the lowest carbon reductions, because the direct use of high temperature HRSG steam for district heat is exergetically expensive. Option A outperforms B which indicates that, in this case, economies of scale are more important than modular commitment. Option A shows that a well placed gas turbine can reduce carbon emissions by more than 30% and with negative abatement cost — and can yield a further reduction of 10%-points with an average abatement cost of less than 10 €/tCO2 by simply *revising* the unit commitment policy.

Operational resilience through system diversity. The same study also found, as part of a sensitivity analysis, that the utility could better respond to a greater range of external conditions, including *fuel* price risk, by adding components which complement rather than replicate current facilities.

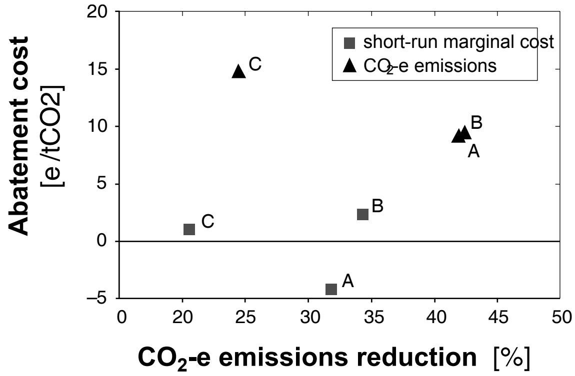

Figure 5: Gas turbine options A–C operated for a representative year under conditions of short-run marginal cost (SRMC) minimization and CO_2-e minimization.

System integration as a virtual resource. This conclusion is a generalization of the previous four points. Improved system integration, possibly as identified using integration modeling, can be viewed as a valuable resource — albeit a virtual one — in its own right. Moreover, as figure 5 indicates, a change in operational objective can give rise to competitive carbon abatement. It would be interesting to know whether adaptively set CO_2 constraints added to electricity dispatch algorithms could yield a similar outcome.

In summary, ESSS possess certain characteristics — known broadly as *network effects* — which appear to accentuate, and occasionally mitigate, the phenomenon described in this section: (1) a networked structure within which key plant (including transmission links) can *saturate*, (2) *high* and often *sunk fixed costs*, (3) private entitlements, including water rights (for hydro) and transmission corridors which are *contextually unique*, (4) *temporal offset* between demand and low-penalty supply, and (5) redundancy in terms of *marginal supply chain* selection (as expressed by unit commitment). Notably, point 2 enables large operators to *strategically price* to exclude entrants, point 1 facilitates a form of competition deficit known as *locational market power*, and point 3 indicates that public-process licensing may be desirable. The observations just given indicate that network effects are as much institutional as they are infrastructural. Agent-based modeling is suited to the study of institutional issues and *deeco* to network effects — hence a combination of both could create a valuable platform on which to study behavior-oriented energy policy formation.

The numerical studies above, plus two others [9,12], indicate that DR measures are sensitive to good integration. And whilst participants in the wholesale domain enjoy substantial institutional support (both public and collective private) for integration benefit reallocation, few parallels exist in the retail domain. This may go some way to explaining the slower than expected uptake of DR — a position which contrasts with that provided by conventional wisdom. Such wisdom instead cites technical and economic entry barriers, asymmetric negative externalities, and orthodox market failure as the key reasons for poor penetration.

5. Network-aware price discovery

This section indicates how network-aware *fuel* price discovery might be implemented within a high-resolution integration model. The arrangement presented is based on the high voltage (HV) wholesale electricity *nodal pricing* system currently used in New Zealand. The method given is suitable for sub-HV retail domain LEP problems whereby the wholesale market can be contained within its own model block (or module). The more general problem in which such markets overlay components of a model is not considered.

The New Zealand scheme comprises about 250 nodes, of which 150 are grid-exit points (GXP). Prices are set on a 30-minute basis. The protocol is structured as an LP problem. The algorithm embeds a capacitated DC power-flow model of the HV network, takes 5-step-increasing supply and demand bids for each interval, and maximizes the value of trading. Quadratic transmission losses are modeled using 5-step-decreasing efficiency curves. Transmission capacities are set by engineering judgment. Participants receive or pay the calculated system marginal price (SMP) for their node and not the (quantity-dependent) price they bid — a situation never to their detriment. As events in New Zealand (2000) and California (2000/01) have shown, nodal pricing can be highly volatile.

The implementation of this procedure within *deeco* should be straightforward, due to its object-oriented structure and the presence of an LP-supporting solver. The appropriate GXP node would be selected to interface with the rest of the model. Figure 6 indicates this arrangement. Certain second-order effects must necessarily be excluded — the most significant for New Zealand relates to influence of demand change on hydro-reservoir management.

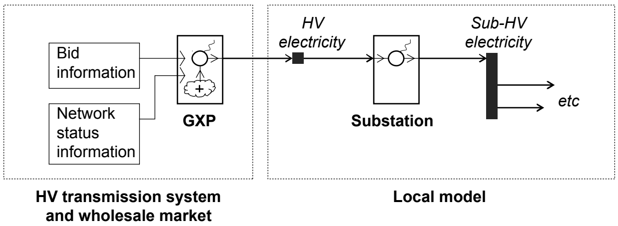

Figure 6: The connection between a nodal pricing block and a local energy planning problem.

There is another reason — besides local demand-dependent price discovery — for including nodal pricing within an integration model. Each GXP node has an associated *marginal generator* which can be assumed to set the transmission-loss-adjusted non-monetary costs associated with marginal demand. This then removes the need to select a single generator type to proxy the abutting HV network, as happens now. The inclusion of a wholesale electricity pricing module would place *deeco* alongside a number of electricity sector techno-economic models.

6. Closure

This paper presents an exergy-services supply system decision-support model — one which classifies as *high-resolution integration modeling*. The model is able to detect certain forms of emergent property in a relatively complex municipal energy system subject to single and multiple interventions. One emergent property concerns improved operational resilience under external variability. Another emergent property involves sub-additivity amongst interventions motivated by climate protection outcomes. Whilst high-resolution integration modeling has yet to be applied to national policy formation, it is reasonable to expect that similar policy conflicts would arise. The prospect of counteraction between sustainability-driven energy policy interventions is of concern. The investment horizons and path-dependencies involved means that the influence of ill-considered policy formation could persist for years or decades. One can also speculate that integration deficits will become more prominent as distributed resource interventions become more deeply embedded into existing systems. The development of integration model-informed *agent-based modeling* may help to identify protocols and incentives which better align commercial and public interest in the area of *fuel* and exergy-services provision.

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