Annals of Operations Research 121, 151–180, 2003

High-Resolution Modeling of Energy-Services Supply Systems Using *deeco*: Overview and Application to Policy Development

THOMAS BRUCKNER and ROBBIE MORRISON* {bruckner, morrison}@iet.tu-berlin.de
Institute for Energy Engineering, Technische Universität Berlin, Marchstraße 18, D-10587 Berlin, Germany

CHRIS HANDLEY chandley@cs.otago.ac.nz
Computer Science Department, University of Otago, PO Box 56, Dunedin, New Zealand

MURRAY PATTERSON m.g.patterson@massey.ac.nz
School of Resource and Environmental Planning, Massey University, Private Bag 11-222, Palmerston North, New Zealand

Abstract. Contemporary energy policy problems typically involve issues of (1) technology selection, placement, and scheduling, (2) energy-services demand modification by location and time-of-use, and/or (3) new sourcing options including emerging renewables. The high-resolution energy systems modeling environment *deeco* (*d*ynamic *e*nergy, *e*missions, and *c*ost *o*ptimization) naturally captures interactions between these components. *deeco* can assist with the search for policy sets which reduce CO_2 and/or displace depletable resource use and which take advantage of cost-effective system integration synergies. The network management objective may be treated as an exogenous variable and process performance can depend on the thermodynamic intensive state of the system. Numerical studies indicate that multiple policy interventions cannot be assumed to be independent and that staging can be significant.

Keywords: national policy support, local energy planning, network optimization, exergy analysis, heat transport and thermal storage, climate protection

AMS subject classification: 90B10

1. Introduction

Abbreviations

CCE	cost creation equations (set);
CO_2-e	carbon dioxide equivalent (emissions) (see footnote 1);
deeco	*d*ynamic *e*nergy, *e*missions, and *c*ost *o*ptimization;
IAS	influential attribute setting (algorithm);
IOR	input/output relationships (set);
MFSN	multi-commodity flow and store network;

* Author for correspondence.

SFEP steady-flow exergy process;
STE state transformation equations (set);
UCP unit commitment procedure.

The energy sector in most Western jurisdictions is facing a number of technical, structural, institutional, resource depletion, and environmental challenges.

Market liberalization programs, now well advanced in a number of countries, place new emphasis on commercial processes for system operation across a range of time-frames, improved supply-side asset utilization, greater customer-domain flexibility, and increased reliance on price-mediated system control. The full implication of these reforms has yet to be determined – both in terms of opportunities for sustainable energy and the degree to which new public interest interventions will be needed to cope with emerging problems.

Alongside such programs, governments are taking a new interest in national and local energy policy formation, with emphasis on demand-side measures, system-wide efficiency, supply diversity, and renewables uptake [15–18,30]. This interest is largely motivated by concerns over global climate change and supply insecurity.

Technical progress has also been rapid. Dispersed and /or multi-product energy technologies – including wind-turbines, small-scale cogeneration, and stationary fuel-cells – are starting to challenge incumbent architectures [3]. Information technology appears set to play a greater role in the management of distributed systems. And some commentators go so far as to suggest that the structural paradigm may shift in favor of smart light bi-directional reticulation networks with highly decentralized control.

Systematic policy formation techniques can help national governments and local administrations deal with their various energy policy challenges. These techniques span a range of time-horizons. At one end, long-range policy models attempt to capture key macroeconomic, technical, and environmental dynamics over decades, whilst, at the other, operational policy models attempt to support and guide the formation of specific policy initiatives. The relationship between different classes of model is complex and evolving, but, at the least, operational modeling should be informed by the conclusions which arise from long-range modeling. This paper restricts itself to policy issues best served by operational policy modeling and the word ‘policy’ is duly interpreted in this light.

A number of single issue public policy interventions, aimed at reducing CO_2-e emissions and/or improving supply diversity, have met or exceeded their specific policy targets – for instance, guaranteed feed price and dispatch regulations in Germany have helped establish 8000 MW of wind capacity in just 10 years.[1]

But the wider question of sustainability policy coordination across the energy sector has yet to be tackled effectively. The question of important interactions between multiple policy interventions – be they synergistic or counteractive – has largely escaped

[1] ‘CO_2-e’ stands for ‘CO_2-equivalent’ and represents the six greenhouse gases identified in the UN Framework Convention on Climate Change (UNFCCC) weighted by their respective 100-year global warming potentials (GWP) relative to carbon dioxide.

notice. For instance, the European Commission research framework covering the "integration" of distributed generation (DG) and renewable energy sources (RES) in energy supply systems [19] provides one such example. This initiative is almost entirely restricted to issues concerning the addition of DG and RES to *status quo* networks and fails to consider the merits of synergetic complementary change within the parent system – using measures in parallel like insulation retrofit and demand-shift. Furthermore, the policy derivations sought appear to be limited to those which facilitate generation technology deployment. Admittedly, the European Commission green paper on energy security [18] does raise the issue of purposeful demand modification, but for reasons of allocation under constraint and not to further sustainability objectives.

The scientific literature on systematic energy policy formulation techniques – be it for national or local policy – which adequately captures the important characteristics of interacting systems modifications is likewise extremely limited. This may simply reflect the fact that most energy models lack the temporal resolution and technology support to investigate such problems effectively. Electricity planning models can examine issues relating to the generation mix, for instance, but are not able to traverse questions of integration which extend beyond the domain of the electricity sector.

Hence, the policy coordination problem remains deep and even seemingly straightforward concepts such as aggregate energy efficiency have escaped consensus definitions thus far [38]. The public policy challenge is, therefore, to formulate a set of internally consistent incentives and sanctions which will realize overarching policy goals and which are effective in context of prevailing market structures and technological opportunities. Due to the present form of market liberalization, cooperation-based strategies have received little attention to date. One such opportunity concerns the agreed modification of unit commitment protocols such that cost-effective system-wide CO_2-e emissions reductions can be captured.

Innovative numerical energy models will necessarily play a central role in this overall endeavor, if only because the interactions are too complex for intuitive analysis. Nonetheless, model selection introduces its own set of issues, not least because the structure of each model type determines the form in which the policy issues under investigation can be framed, analyzed, and directed.

This paper presents one such energy model, *deeco*, whose two principle strengths – from the viewpoint of policy analysis – are as follows. Quantitatively, the ability to identify policy outcome integration deficits and to assist with the search for useful policy synergies. And qualitatively, the concepts behind *deeco* provide a cogent high-level interpretation of the policy formation problem, at least as far as system integration-related issues are concerned.

The following semantic distinction is adopted for convenience: the phrase '*deeco* modeling environment' – or simply '*deeco*' – is used to describe the application program as it stands *plus* the concepts contained therein *plus* those methodological extensions currently being implemented. In contrast, a '*deeco* model' – or simply 'model' – refers to an individual problem being subject to analysis.

2. The *deeco* modeling environment

The unix application program *deeco*: *d*ynamic *e*nergy, *e*missions, and *c*ost *o*ptimization was developed by one of the authors during 1992–1995 [7].[2,3] Since its release in late-1995, a further four research projects have made significant contributions to the original code-base.

deeco classifies as an energy systems decision-support model that uses – as its two principal foundations – extended input/output engineering relationships to represent constituent technologies and a high-resolution optimization-controlled commodity flow network to provide structure and scheduling protocols. *deeco* can be used to evaluate a variety of proposed system modifications in terms of their collective impact on selected cost categories over some nominated time-horizon. *deeco* is well suited to inter-seasonal studies, spanning perhaps a maximum of two years.

Important attributes of the method, which may also serve to differentiate it from related modeling initiatives, include: high temporal and topological resolution – the default time discretization is one-hour $\times$ one year, demand framed in terms of energy-service, support for attribute-characterized heat transport and thermal storage, use of network management objectives other than financial cost, and the ability to identify integration deficits within sets of interventions.

The method itself can be applied to national, local/municipal, and remote area energy policy development. It is systems architecture neutral yet suitable for issues involving dispersed technologies and measures, including demand modification. Conversely, the method currently does not capture internal feedbacks as might arise from price/demand sensitivities or technology maturation and hence is not suitable for issues that involve economic and/or structural evolution. Neither is *deeco* designed to replace detailed engineering and financial project assessment, nor compete with electricity sector load management packages.

Energy policy models can be classified as being primarily process-based and financial/technical *or* primarily sector-based and economic. *deeco* aligns with the first. Pure process-based policy modeling can attract criticism for its lack of price discovery and elasticity mechanisms. However, the inclusion of such mechanisms within *deeco*-type modeling introduces a number of conceptual issues. The price discovery mechanism would need to operate at the same temporal and topological resolution as the underlying technical model. This means price volatility cannot be treated as noise and simply filtered. Nor can market failure arising from serendipitous and gamed monopoly status and capture be dismissed as minor (witness events in California 2000/01 and New Zealand 2000). Further, consumer price exposure is often attenuated through hedging and capping mechanisms, whilst short-run price inelasticity appears to be the norm on the demand-side. Hence, a number of important assumptions and strategies used in

[2] The *deeco* project website is currently located at: `http://www.iet.tu-berlin.de/deeco`. A number of academic and technical documents can be downloaded from this site.

[3] As at November 2002, the release version of *deeco* was S04. *deeco* runs under SCO UnixWare 2 and 7 and Linux (Kernel 2.4).

sector-based modeling are difficult to sustain when the modeling resolution increases. One response would be to adopt agent-based modeling techniques, whereby key players are explicitly included and characterized using observed behaviors – in which case, certain conventional economic modeling assumptions are not required. Process-based and agent-based modeling share a similar "bottom-up" modeling philosophy.

The motivation for developing *deeco* and for undertaking the type of modeling under discussion is to meet a real deficit in energy policy support tools which can be applied to *fine-grained* and usually *multi-faceted* policy problems – and particularly those which seek to improve sustainability outcomes. The term 'fine-grained' indicates that system performance is sensitive to variations in temporal and/or topological structure – in other words, scheduling and placement matter. And 'multi-faceted' refers to the fact that certain interactions can arise within a particular set of modifications and the underlying system. These interactions are generally counter-intuitive in the sense that the overall effect of a given set of modifications need not necessarily be the sum of the individual contributions. Rather, the result may be sub-additive or super-additive – counteractive or synergetic, respectively [9]. Furthermore, these interactions are likely to be more pronounced when sections of the architecture operate near or at capacity.

The form of system upgrade path – as represented by a sequence of modifications – can likewise be important, particularly when most system investments must be regarded as sunk. Preliminary experiments using *deeco* indicate that incremental, locally-rational decisions can produce poor conclusions and may well *lock-out* potentially higher-performing options in the future [10,44].

The relationship between *deeco*-type modeling and energy policy support can be viewed as a two-stage problem: the first step is to determine a set of energy system modifications considered desirable in light of stated public interest goals. And the second is to develop incentives and sanctions which facilitate the uptake of said modifications and/or which distribute emergent benefits and associated costs equitably amongst participants. *deeco* can assist with the first step although not the second.

A number of practical issues arise when applying *deeco* as would with any modeling exercise. These include the question of how well on-the-ground schemes and procedures align with given *deeco* scenarios and the degree to which any such discrepancies matter. Furthermore, some policy measures may simply fail to produce the desired response in stakeholders. And other measures may require cooperation amongst system participants and could be susceptible to corruption by inapt unilateral action. These and related questions lie outside the scope of this paper, yet they are issues that individual model users must answer for themselves. Hence, *deeco*-type modeling should be regarded as a useful but not sufficient condition for realizing across the board improvements.

Potential system modifications can comprise any combination of so-called *physical* responses – for instance, inclusion of innovative conversion processes, uprated plant performance, or revised architecture – and *informational* responses – such as demand modification or amended unit commitment policy. *deeco* itself treats incumbent and proposed technologies and other interventions equally and no individual option is accorded a preferential dispatch status, once the system management objective has been set. Supported objectives include CO_2-e emissions reduction and reduced depletable resource use. The system management objective – which can be treated as an exogenous variable – and the sought policy outcome need not be the same, although the sought policy outcome will be necessarily better if they do.[4]

Demand should, where possible, be defined in terms of energy-service provision, as characterized by an appropriate intensity – for example, air temperature in the case of space-heating or lux levels for illuminance.[5] This approach facilitates a much greater set of potential responses to the question of supply, including the use of energetically-passive techniques – for instance, retrofitted insulation [41] and daylighting. In some cases, energetically-passive techniques can be modeled as explicit *virtual* supply plant.

Sourcing, conversion, and storage technologies currently supported by *deeco* include: conventional furnaces and boilers, steam manifolds, back-pressure and condensing-extraction steam turbines, standard and combined-cycle gas turbines, reciprocating engine cogeneration plant, gas-motor, electric, and absorption heat-pumps, condensing boilers, heat-exchanger systems for waste heat recovery, short and long-range district heating grids, stratified thermal storage, super-conducting power storage (experimental), solar thermal collectors, wind-turbine generators, photovoltaic arrays, and domestic space-heat demand. The related energy carriers include: natural gas, oil, coal, hot-water, steam, electricity, and mechanical power.

deeco itself consists of two parts: a central *kernel* which provides the network structure and associated unit commitment procedure (UCP). And a *library* of plant modules from which individual plant are instantiated to populate a specific model. As will been seen, this two-part separation manifests both programmatically and conceptually.

The UCP organizes the use of plant within the model. The UCP provides a method of scheduling plant to best effect as the time-horizon unfolds – in a certain sense, the UCP acts as a proxy for some hypothetical system operator. A particular UCP comprises suitable optimization routines together with some selected management objective, and can include prescribed (as opposed to declarative) rules as well. The design of UCP draws on algorithmic graph theory and combinatorial optimization (see section 9) [13, 20,45].

The plant themselves are primarily characterized – from the point of view of the network – by input/output relationships (IOR). These IOR yield information about the associations between commodity flows entering and exiting individual plant and this information is used by the UCP. IOR also contain information about upper flow capacities and minimum flow requirements. Flows may be displaced in time through the use of

[4] This paper adopts the systems theory definitions of ‘parameter’ and ‘variable’, which equate to the economics modeling terms ‘exogenous variable’ and ‘endogenous variable’, respectively.

[5] Extensive state variables/parameters or simply ‘extensities’ are those quantities which scale with system size. Examples include: mass m, volume V, and, in some cases, capital requirement K. Conversely, intensive state variables/parameters or ‘intensities’ are independent of system size. Examples include: absolute temperature T, absolute pressure p, altitude z, velocity v, chemical potential for species i, μ_i, specific cost for characteristic j, c_j, and unit commodity price p. Extensive variables need not be conserved.

storage. IOR can be considered as a generalization of the notion of plant efficiency. Strictly speaking, plant efficiency is defined using only flows, one *currency*, and steady-state operation – thereby yielding a dimensionless number. Here, 'currency' refers to the extensity used to characterize a particular commodity flow or stock, as discussed in section 7.[6] IOR, on the other hand, can use mixed *currencies* and can entail inventories as well as flows.

IOR are refreshed for each time-interval, in light of prevailing environmental conditions such as ambient temperature, current and prior plant state information, and in certain cases, flow intensities passed from neighboring plant. These particular flow intensities are called *influential attributes* and are resolved using the influential attribute setting (IAS) algorithm. IOR can be regarded as *reduced-form* simulations. The procedures that generate IOR may be derived from empirical data, established using information found in engineering design guides, or inferred from more sophisticated stand-alone simulations built using process simulation software – such as `GateCycle` from GE Enter Software or `TRNSYS` from the University of Wisconsin–Madison.

One of the strengths of *deeco* is that – subject to certain tractability requirements – the influence of flow and store intensities can be factored in whenever certain values are required and/or the IOR themselves could be substantially affected. For example, the *return* temperature in a recirculating-media condensing boiler space-heating system can affect boiler conversion efficiency to the point where this influence warrants inclusion. The recommendation that energy models use intensive as well as extensive state variables is due to Kühner [35]. In contrast, most generalized energy models do not support dependent intensities and are therefore obliged to treat "heat", for instance, as an undifferentiated commodity and "heat storage" as a stack process in the computer science sense, albeit one that can deflate over time.[7]

deeco models are normally interpreted comparatively – which means that decision-support information is provided in terms of absolute or percentage difference with some predetermined estimate of business-as-usual (BAU) practice. Commonly used cost categories, which are tallied and reported on completion, include CO_2-e emissions, depletable resource use, and levelized financial cost (often with existing investment treated as sunk). As noted earlier, potential system modifications can take various forms. Changes to plant characteristics, network connectivity, and/or demand profiles are self-evident. But less obvious is the ability to re-specify the network management objective and/or modify the form of the UCP in use. In fact, UCP modification may well furnish worthwhile Kyoto responses – a question currently under investigation. Astute users can also embark on a second tier of 'optimization' in the sense that under-utilized plant can

[6] The term 'currency' is set in italics to indicate that it has been given special meaning.

[7] Whilst the notion of *heat* has a formal definition in thermodynamics, the word is commonly used in a more general but less precise context. This paper adopts the following compromise in the interests of readability: the phrases '(recirculating media) heat transport' and 'thermal storage' stand for 'logical commodity flow characterized by physical flow exergy $\dot{E}_X$ and valued for net-heat transfer' and a 'commodity stock characterized by physical nonflow exergy $\boldsymbol{E}_X$ and valued for time-displaced heat transfer', respectively. See [4] for an exergy-based treatment of thermal storage.

be re-specified or even removed and the model rerun – a process which can be automated using scripted programming. *deeco* can also be used to benchmark the performance of an existing system by contrasting actual practice against model output.

One interesting application for *deeco* is the assessment of "additionality" under Kyoto Protocol Flexibility Mechanisms or under certain country-specific early action reward schemes. The term 'additionality' derives from the Kyoto Protocol, which includes provision for emissions reductions that are "additional to any that would (otherwise) occur" (refer to Articles 6 and 12). *deeco* can help determine the point and degree to which CO_2-e reducing modifications become financially unattractive and hence additional.

But not only can *deeco* provide useful numerical results, the concepts on which it is based are instructive in their own right. For instance, a number of public policy issues often treated as separate – such as system-wide energy efficiency ("rational use of energy"), renewable energy sourcing, demand management, use of storage, heat recovery, and amended operational policy – can be interpreted as interdependent components of the more general problem formulation being presented.

3. Related initiatives

deeco is cast in this paper as a tool for public policy support, although other applications, including that of engineering scheme design support, are also feasible. In its public policy role, *deeco* lies between industry-specific planning tools and longer-range national policy models. Bunn and Larsen [11] review this latter category.

A number of established national policy models are, like *deeco*, optimization-based and embed infrastructure capacity limitations. These include: `EFOM` [22], `MARKAL` and extensions including `TIMES` [21,49,52], `MESSAGE` [42], and `AIM/end-use` [31, 32]. Some of these models have also been applied to analyze municipal systems – for instance, `MARKAL` to Geneva, Gothenburg, Mannheim, Turin, and cities in Puerto Rico and `AIM/end-use` to Beijing.

The policy modeling initiative which most closely resembles *deeco* in terms of structure and application is `MODEST` from Linköping Institute of Technology, Sweden [28,29,55,56]. The principle differences relative to the current release of *deeco* are: support for inter-temporal use-of-storage optimization, lower temporal resolution and hence loss of potentially important supply/demand correlations, and less sophisticated process modeling.

The engineering design-support tool which most closely relates to *deeco* is `PRODESign` from the Energy Research Centre of the Netherlands (ECN) [12]. `PRODESign` aligns with the optimized dynamical network component of *deeco* yet lacks much of the thermodynamic sophistication including the use of dependent intensities (influential attributes). But like *deeco*, `PRODESign` supports non-financial cost optimization, which is a rare feature. And although `PRODESign` is cast as a design-support tool, it could well be used for policy investigations.

The Department of Energy Systems Engineering, Osaka Prefecture University, Japan has also applied inter-temporal optimization to a generalized energy system design problem [60]. Their approach uses decomposed MILP (mixed-integer linear program) techniques, but even so, computational limitations restrict the method to hourly intervals spanning a matter of days. Therefore, typical winter, summer, and mid-year periods must be chosen, and longer timeframe inter-temporal issues, such as seasonal storage, cannot be investigated.

4. *deeco* project review

The *deeco* project originated at the Institute for Theoretical Physics, Würzburg University, Germany. The project ultimately derives from work started in the late-1980s which examined the potential for cascaded heat reuse within national economies [27,57] and regional systems [24]. *deeco* itself was written as part of a PhD project [7], first released in late-1995, and ported to an Intel-compatible platform during 1998 [43]. The mathematical specification used to code much of *deeco* is reported under the acronym NEMESS [25]. Relevant university theses and publications which predate *deeco* comprise [6,23,36,37,51] whilst later material based on *deeco* includes [9,10,26,39–41,43,44,48]. Comprehensive user documentation for *deeco* is available in German [8]. The software is now under active development at the Institute for Energy Engineering, Technical University of Berlin, Germany.

The current release of *deeco* is written in C++ [14], comprises 18 000 lines of code, some 75 user-defined classes, and 3-deep inheritance. UNIX Systems Laboratories (USL) Standard Components (SC) libraries provide graph support [59] and a modified version of the simplex routine from Numerical Recipes is used to solve the combinatorial problem [47]. The bulk of the programming effort went into the design and implementation of plant modules.

Run-times are in the order of one hour on a 1000 MHz commodity PC with 512 MB of memory, given the following problem metrics: 30 plant with up to 10 constraint equations each, 90 decision variables with most from the 80 connections, 8760 hourly intervals, inclusion of thermal storage, and time-myopic optimization only.

Three published research studies have made use of *deeco*. Bruckner et al. [9] present a proof-of-concept analysis which investigated investment options for a south German municipal utility supplying cogenerated district heat and power. Linderberger et al. [39] describe engineering design support for a green field solar-assisted district heating scheme with seasonal thermal storage (coded SOLEG). Linderberger and Kümmel [41] describe a facilities modernization project which evaluated switchable dynamic insulation options (coded ISOTEG). In all cases, financially cost-effective CO_2-e reductions were sought through better technical integration.

In mid-2001, a new 5-year research project commenced which will apply *deeco* to national policy formulation. New Zealand has been selected as the case-study due to certain interesting characteristics: island status meaning limited external linkages, low (mesh) diversity reticulation, significant constraint issues, good prospects for new renewables, and government commitment to ratify and meet a Kyoto Protocol target of zero-percent. The next section co-opts aspects of this project to illustrate *deeco*.

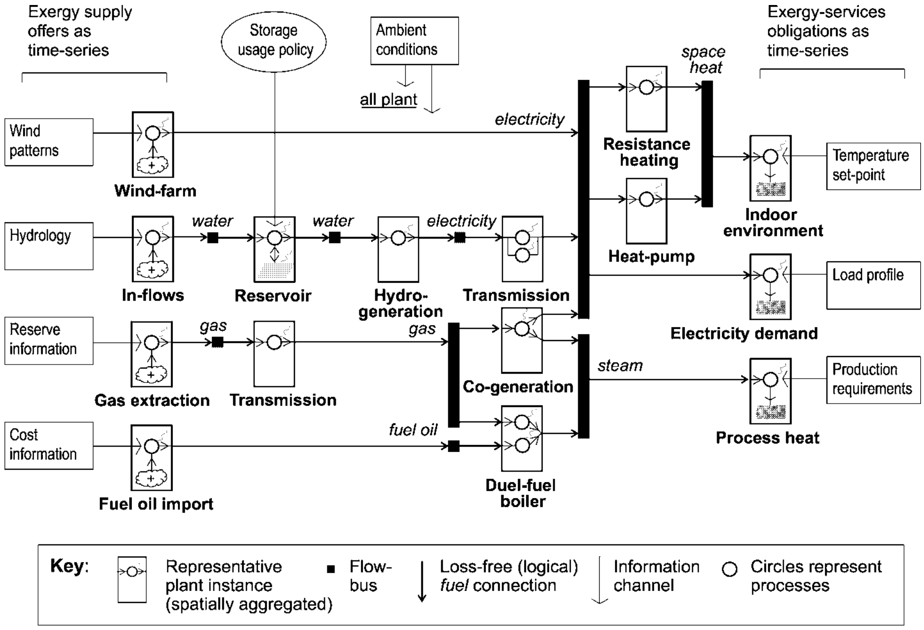

Figure 1. New Zealand gas and electricity model prototype provided for illustrative purposes. 'Exergy' is described in section 7.

5. Illustrative example based on a gas and electricity sector model for New Zealand

Figure 1 shows a *deeco* schematic which gives a simplified view of the New Zealand gas and electricity sectors – important demand categories have been omitted and the depiction is highly spatially aggregate.

Some important observations can be derived from figure 1. The various exogenous exergy-services obligations time-series on the far right-side *drive* the problem.[8] For each time-interval, these obligations are converted to demand information that is transferred leftward. The exogenous exergy supply-offers time-series on the left-side provide information about current sourcing options – including imports from abutting networks (in this case, the *fuel oil import* block). The demand signals are *routed* right to left in accordance with the UCP in place, or – equivalently – a set of plant utilizations is determined. As yet unspecified topical policy issues are to be investigated with a more sophisticated version of the model shown, including the relative merits of various collectively evaluated energy efficiency and renewable energy support programs.

[8] Colloquial usage of the word 'energy' aligns more strongly with the concept of exergy than with any other related notion. For instance, an Oxford paperback dictionary [54] gives the technical definition of *energy* as the: "capacity of matter or radiation to do work". Ayres [1] also makes the same observation. Those unfamiliar with the term 'exergy' can mentally substitute 'energy' as they read.

6. Model specification and model output

A *deeco* model specification is made up of a *reference case* together with a suite of one or more sets of proposed modifications, called *scenarios*. The reference case may embed projections regarding anticipated change. The reference case itself is composed of information concerning: *network architecture* comprising details sufficient to specify all plant, flow-bus, and connection instances (as defined in section 8) – *system context* comprising time-series for ambient conditions (often intensities), demand for energy-services (or failing that, outright energy) profiles and institutional constraints – and certain *exogenous variables* including the default management objective, financial discount rate, and opening and closing stock inventories. A new scenario can be created by altering any entry in the reference case. Sensitivity analysis may be performed by 'disturbing' either the reference case or any of the derived scenarios and re-running the analysis.

deeco outputs aggregate information concerning the cost categories mentioned earlier, plus time-series for individual plant utilizations. This latter information is not intended for interval-by-interval operational use but rather to identify those plant with poor usage/cost ratios for re-specification or exclusion in further scenarios.

7. Choice of currency

One defining issue for *deeco*-type modeling is the choice of *currency* used to characterize the flows and stock of particular *fuels* within the system.[9] The answer is not straightforward and different responses can be given in respect of the conceptual framework underpinning *deeco* and for the construction of the plant modules. The word 'fuel' is used in the sense given in Bejan et al. [5] which covers any useful flow or stock commodity valued for its exergy content, and includes work and heat transfer. The terms 'energy' and 'exergy' are not used as resource descriptors in this paper as far as is possible and their usage is reserved for their respective thermodynamic functions (a similar relationship exists between matter, mass, and moles). A given *fuel* need not necessarily exhibit nonzero economic opportunity cost. The main theoretic consideration concerning the choice of *currency* is that it be a nonzero extensity yet it need not be conserved. Moreover, each identified *fuel* within a network can be represented by a different *currency* type. The core algorithms within the *deeco* kernel are indifferent to the choice of *currency*, although the plant modules require local resolution.

From the conceptual point of view, *deeco* is best framed in terms of *exergy* and the remainder of this paper will use exergy by default. Exergy is a development from engineering thermodynamics [2,4,34] and represents the potential of a flow or stock commodity to produce work – as opposed to heat at ambient temperature – in context of the prevailing physical and chemical conditions (the *dead-state*) and feasible conversion processes. The commodity itself and the environment will need to be represented using

[9] The term 'fuel' is set in italics to indicate that it has been given special meaning as discussed in this paragraph.

bulk intensities. One benefit of the exergy formulation is that commodity flows thus characterized must necessarily be *antiparallel* to the propagation of demand information within the system (in all but some nonsensical situations) – this is not always true when such flows are characterized in terms of energy, for instance when dealing with sub-ambient cooling utility. *deeco* is interpreted in terms of exergy exchange in [43].

Another candidate for use as a *currency* is *energy* referenced to the same physical and chemical conditions and feasible conversion processes requirement as would apply to exergy assessment. From a pragmatic standpoint, however, the energy assessment of industrial fuels is normally referenced to more or less standardized laboratory conditions, although there remains no agreed treatment for pre-existing and combustion water condensation [46].

The plant module library in the current release of *deeco* is constructed on the basis of energy, using LHV (lower heating value) and the 'laboratory' compromise where necessary. However, as noted, a common currency is not mandatory and it may make better sense to adopt non-energy extensities in some circumstances – for instance, the use of volume flow $\dot{V}$ (in m^3/s) when dealing with hydro-reservoir extraction.

8. The core structure of *deeco*

This section presents a more formal description of *deeco* as it stands. Previously unpublished material includes: the use of exergy analysis to generalize foundation concepts, the use of thermodynamic intensities as model variables, and the use of object-oriented design methods to assist with problem abstraction and program structure. To our knowledge, these themes have not been discussed in the literature for any implemented energy policy model. General background is provided in [25], otherwise consult [7,43] for more on the topics just listed.

As indicated earlier, the implementation of *deeco* consists of two parts: a central kernel and a library of plant modules. The kernel contributes the network structure, core algorithms, and certain housekeeping tasks like data input/output, whilst the plant modules provide support for the various technologies and *fuel* types.

Some comments on *fuel* connections and plant are in order at this point. Modeling convenience requires that *fuel* connections be represented by just one extensity which also serves as a decision variable. This means that multiple path *fuel* transport mechanisms need to be abstracted by single *logical* connection – logical in the computer science sense.[10] For instance, two-pipe recirculating media heat transport will need to be recast as a single logical heat transport flow. And a 4-cable 3-phase AC electricity connection will need to be recast as a "one-line" power flow [50]. The notion of *plant* refers to a real-world entity that has a definable function, identifiable thermodynamic losses as represented by exergy destruction, and generates financial and non-financial costs as a result of existence and/or usage. The identification of plant boundaries and

[10] The term 'logical' in this sense means non-physical or conceptual yet underpinned by something physical or actual.

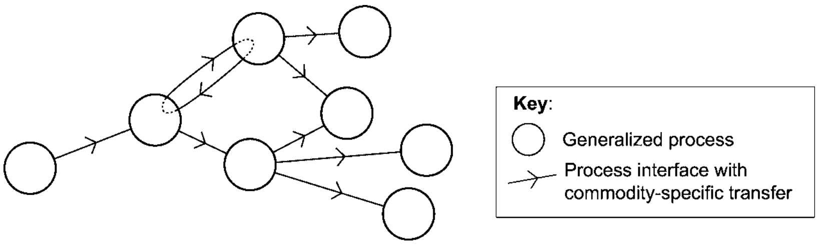

Figure 2. A multi-commodity flow and store network (MFSN) with all flows strictly physical at this stage. This entity provides the basis for the network structure within *deeco*. Sets of edges carrying coupled flows – as indicated here by the dashed lines – will need to be recast as single logical edges. Also, further physical aggregation and/or aphysical disaggregation (to facilitate piecewise linear approximation) of the contained objects may yield model building benefits. The MFSN need not be planar or contiguous as is depicted.[11]

connections and the determination of plant function and performance are conceptually inseparable.

8.1. Two lines of thought

deeco can be interpreted as deriving from two lines of thought – the first draws on the concept of *network optimization* from operations research (OR) and the second on the concept of the steady-flow *exergetic process* from engineering thermodynamics. Both concepts need to be recast in their respective dynamical contexts. These two notions are then combined and the resulting picture, although conceptually complete is, unfortunately, not universally tractable. As a consequence, a number of conceptual reductions are required to produce a workable model, and these simplifications are discussed as they arise.

8.2. The multi-commodity flow and store network (MFSN)

The primary OR contribution is the multi-commodity flow and store network (MFSN) – multi-commodity in the restricted sense that a given edge cannot carry more than one kind of commodity. Figure 2 shows such an entity. The flows are naturally directional, making the resultant graph directed. Furthermore, figure 2 is drawn such that all flows are strictly physical, which means that certain flows may need to be recast as logical, as described earlier.

The MFSN – ignoring, for the moment, the objects it contains – is fully characterized by a set of extensive variables, each one in a *currency* suitable for the commodity flow or store it represents. Conversely, no intensive variables are required – a point which highlights the fact that the intensities within *deeco* arise from thermodynamic and financial considerations. Hence, the extensities collectively define the state-space associated with the MFSN structure.

[11] A 'planar' graph is one which can be drawn without requiring links to cross or, more formally, the graph can be embedded on a surface of genus zero.

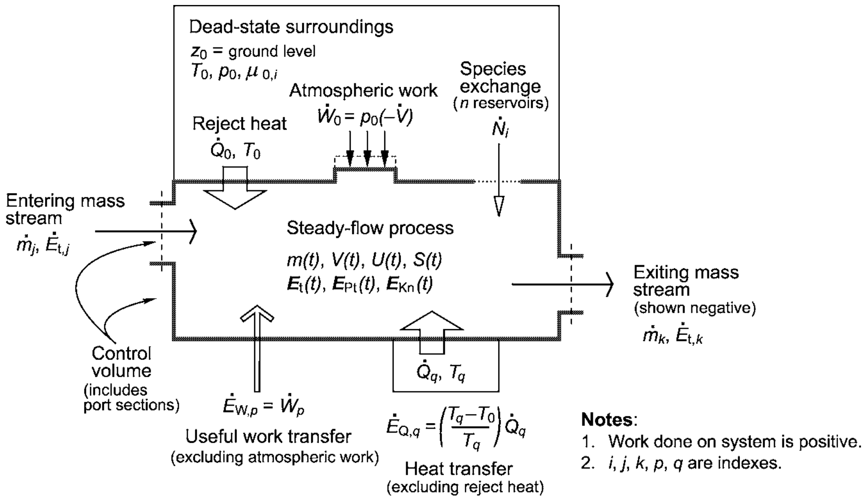

Figure 3. A generalized steady-flow exergetic process (SFEP) whose extension as a dynamical entity would be interpreted as a sequence of *non-stationary* SFEP. This entity is the building block from which plant are formed and from which *fuel*-based commodities are categorized. Some notation is given in footnote 12, otherwise the symbols have their usual meanings. *Source*: adapted from [4, chapter 5].

The objects within the MFSN – which, as will be seen, are the thermodynamic processes – are assigned their own individual (sub-)state-space in the manner indicated by Karlqvist [33]. An MFSN classifies as *dynamical* if any one of the objects it contains is itself dynamical. The inclusion of storage will have this effect.

8.3. The steady-flow exergetic process (SFEP)

The primary contribution from engineering thermodynamics is the generalized steady-flow – but not necessarily steady-state – exergetic process (SFEP). This object constitutes the central building block for non-continuum exergy analysis, for which Baehr [2], Bejan [4], and Kotas [34] give detailed accounts. Figure 3 shows the general arrangement of a SFEP, an entity which will later be encapsulated to give rise to the notion of plant. The exergy balance equation associated with this diagram, which simultaneously defines exergy in its various forms, can be found in the given references.[12]

The SFEP needs to be interpreted in a dynamical context. This is achieved by constructing a sequence of SFEP specifications – which, technically speaking, means that the SFEP is *non-stationary* from the view-point of *that* entity.[13] Rapid settling

[12] The following forms of exergy can be identified: $\dot{E}_{\mathrm{x}}$, $\dot{E}_{\mathrm{ch}}$, $\dot{E}_{\mathrm{t}}$ or *physical*, *chemical*, and *total* flow exergy associated with material flow; $\dot{E}_{\mathrm{Q}}$, $\dot{E}_{\mathrm{W}}$ or *heat-associated* and *work-associated* flow exergy; $\boldsymbol{E}_{\mathrm{x}}$, $\boldsymbol{E}_{\mathrm{ch}}$, $\boldsymbol{E}_{\mathrm{t}}$ or *physical*, *chemical*, and *total* nonflow exergy; and $\boldsymbol{E}_{\mathrm{Pt}}$, $\boldsymbol{E}_{\mathrm{Kn}}$ or *potential* and *kinetic* nonflow exergy (when explicitly represented). Particular definitions for each are necessarily context-specific which means that it is important to identify and confirm the underlying arrangement before proceeding.

[13] The term 'non-stationary' indicates that the model specification parameters can vary over time. In this case, model refers to the SFEP.

is assumed for most types of process – that is, they possess a short relaxation-time-constant relative to the selected time-interval. This allows dynamical SFEP to be viewed as evolving through a set of stepwise constant states. Storage processes under conditions of exergetic loss and decay do not possess suitably short relaxation-time-constants and *deeco* relies on an adaptive time-step algorithm in order to capture the more leisurely dynamics of storage evolution. This procedure breaks the time-interval into successively smaller time-steps in order to produce a sufficiently accurate discrete approximation for the differential equations which describe state change.

In general, a time-local SFEP can be characterized by an appropriate *set* of one extensity and one or more intensities covering each discrete flow and store. SFEP are thereby treated as discrete composite systems – as opposed to continuum systems – at least in terms of their nominated flows and stores. Discrete composite systems can be regarded as a form of "lumped parameter" approximation. The set of variables just indicated defines the (sub-)state-space associated with each process and its connecting flows and is sufficient for the purpose of SFEP-type exergy analysis. The intensities sometimes carry the qualifier 'bulk' – for instance, *bulk* temperature – to indicate that the appropriate thermodynamic mean value is required and, by implication, that the associated discrete system is assumed to be thermodynamically uniform [4,5].[14]

Fluid media thermal storage usually needs to be modeled using discrete temperature stratification. This can be achieved by dividing the storage media into a number of horizontal cells, each with its own single extensity and set of one or more bulk intensities, including temperature.

The basic arrangement of the SFEP directly informs the classification of *fuel*-based flows and stores within *deeco* and assists with issues related to the specification of flow and store *currencies* – that is, with the selection of extensities. With regard to intensities, *deeco* (as will be seen) adopts a parsimonious approach – electing to quantify *only those* intensities that have a first-order influence on input/output performance and discarding all others.

8.4. SFEP characterization

From the point of view of the network structure – or, more specifically, the UCP – the behavior of a process is fully characterized by its time-locally-resolved IOR and cost creation equations (CCE). In general, a process is dynamical and evolves using its own state-transformation equations (STE). Space considerations preclude a treatment of STE but they derive from discrete-time systems theory. Prior to each time-local UCP call, information from the process state vector $\mathbf{S}^t$ which includes stock inventories, the environmental data vector $\mathbf{U}^t$ (see section 8.10) and, as appropriate, the IAS-resolved influential attributes vector for each connected flow c, $\mathbf{J}^t_{\{c\}}$ (see equation (2)) are used to finalize the process IOR and CCE. This point in time is indicated by the "fully characterized plant"

[14] More precisely, the concept of 'uniformity' requires that the system be macroscopically homogeneous, isotropic, and subject to spatially invariant external fields.

block in figure 5. As indicated earlier, an IOR contains information on flow balance by equality, and on flow bounds by inequality.

As an example, equation (1) describes part of an IOR for a cogeneration process (which will be later encapsulated in a plant entity). During time-interval t, the process receives oxidizable fuel flow $\dot{F}^t_{\text{Chem,En}}$ from an upstream process and dispatches electric power $\dot{F}^t_{\text{Elec,Ex}}$ and heat $\dot{F}^t_{\text{H,Ex}}$ by recirculating media to downstream processes – these three variables being UCP decision variables.[15] This particular process has no storage and cannot buffer flows across time, so the IOR equality reduces to:

$$\dot{F}^t_{\text{Chem,En}} = \psi_0^{\text{Chem}}\big(\mathbf{J}^t_{\{c\}}, \mathbf{S}^t, \mathbf{U}^t, t\big) + \sum_{\alpha\in\{\text{Elec,H}\}} \chi_\alpha^{\text{Chem}}\big(\mathbf{J}^t_{\{c\}}, \mathbf{S}^t, \mathbf{U}^t, t\big)\dot{F}^t_{\alpha,\text{Ex}}, \qquad (1)$$

where: $\chi_{\text{B}}^{\text{A}}$ is the multiplier function for converting *fuel* A to *fuel* B, otherwise known as the *marginal specific fuel expenditure*, ψ_0^{A} is an offset function due to no-load input requirements, known as the *standing fuel demand*, and 'En' and 'Ex' indicated process entering and exiting flows, respectively.[16] The χ and ψ are arbitrary on $\mathbf{J}^t_{\{c\}}, \mathbf{S}^t, \mathbf{U}^t$, and t. Furthermore, the equation, in its general form, is indifferent to the choice of *currency* used to characterize each of the *fuel* flows. Equation (1) is comparable to equation (16) in [25] but now contains influential attribute dependencies due to $\mathbf{J}^t_{\{c\}}$.

8.5. Combining the MFSN and SFEP concepts

The two strands outlined thus far – the multi-commodity flow and store network and the dynamical steady-flow exergetic process – when combined using their most general formulations do not produce a computable model. A number of restrictions are needed in order to produce a framework which is inherently robust yet still widely applicable. The most fundamental assumption is listed first.

Assumption A. Orthogonality of extensive and intensive variables.

The orthogonality assumption requires that intensive and extensive state-spaces be treated as orthogonal.[17]

Assumption A may not be as restrictive in practice as might be imagined. Many of the engineering systems likely to be encountered possess sophisticated control mecha-

[15] Previous literature describing *deeco* uses E instead of F to represent commodity flow. This change of notation was prompted by a desire to avoid clashing with exergy symbols and to provide an opportunity to revise *deeco* equations so that all flows are necessarily UCP variables. In addition, the subscript 'Chem' now replaces 'Fuel' in order to align with exergy analysis classifications.

[16] This treatment specifically, and the paper more generally, takes some notational shortcuts in the interests of simplicity. The indexing normally used to differentiate process-specific variables has been omitted. And the time-interval count t should, for (endogenous) variables, be replaced by the time-step index k. The reason for this is that t and k will no longer match in cases where the adaptive time-step procedure is invoked.

[17] The term 'orthogonal' indicates that the two sets of variables are not coupled in any way.

nisms to maintain their intensive state – for instance, electricity grids normally hold their supply voltage within tight margins.

In some circumstances, local relaxation of the orthogonality assumption may be achieved by introducing iterative extensity/intensity sub-models, so long as these routines converge satisfactorily and do not provoke some wider instability.

It can be noted that, at this point, the MFSN/SFEP combination has a direct physical explanation – that of a not-necessarily-planar patchwork of thermodynamic processes, whereby the edges of the MFSN represent commodity-specific process interfaces and the graph-theoretic dual of the MFSN re-establishes the process system boundaries. This physical explanation will hold only as long as flow-buses remain unamalgamated (see below).

8.6. Object-oriented repackaging of MFSN and SFEP

This section takes the ideas introduced thus far and 'repackages' them so that they better map to real-world entities and/or can exploit certain modeling compromises. This exercise also draws heavily on object-oriented design concepts.

The fundamental building blocks for this new picture are: the *process description* entity (depicted by a circle on *deeco* schematics, see figure 1) – formerly an SFEP and hence also a circle on the MSFN shown in figure 2. And the *commodity flow* entity (depicted by a light arrow) – formerly an edge on the MFSN – or in the case of edges with coupled flow, recast in their logical context and characterized by net-extensity transfer. Unless the context dictates otherwise, the use of the term 'flow' in this paper refers to *commodity flow* as just defined.

It is advantageous to encapsulate these two *primitive* entities within *encapsulation* entities: the *plant* entity (depicted by a box) and the *connection* entity (depicted by a heavy arrow), respectively. Encapsulation provides certain benefits including the ability to bundle additional structure: in the case of plant entities, to group several process description entities in order to better organize the model, and in the case of connection entities, to include dedicated inter-plant communication channels.

It is convenient, again for reasons of conceptual development, to introduce a third entity pair: the *interface* primitive entity (not depicted directly on *deeco* schematics) and its corresponding *flow-bus* encapsulation entity (depicted by a dark square, again see figure 1). The interface entity is added to the mid-point of each commodity flow entity, thereby dividing the commodity flow entity in two. Any interface entity which lies *inside* an associated plant entity does not require an associated flow-bus entity. Connection and flow-bus entities provide a convenient and intuitive way to structure the input dataset.

Flow-bus entities containing identical connection entities – that is, with the same commodity type and with identical characterizing intensities values – may be amalgamated (depicted by a vertical bar). The resulting flow branching and/or flow joining flow-bus entity is strictly aphysical but such amalgamation can represent a useful modeling compromise. The underlying primitive entities will now be collectively represented by a non-trivial flow balance equation. Amalgamated flow-buses are used as loss- and cost-free interconnection plant – although if this approximation cannot be sustained, the offending bus would need to be replaced with an explicit transport plant.

The directed graph or *digraph* duly formed from plant, connections, and flow-buses (dropping the term 'entity' for convenience at this point) is known as the *principal deeco digraph* and is the structure upon which most algorithms conceptually act. The graph is also bipartite due to the requirement that flow-buses interpose plant.

Plant, connections, and flow-buses are represented programmatically as object-oriented class instances. These objects are then contained in a graph object – which also establishes the connectivity integrity of the dataset as a side-effect of construction. In practice, the algorithms within *deeco* operate directly on the plant objects using a traversal list derived from the graph container shortly after its formation (see section 8.12) – this strategy is simply a programming convenience.

From the point of view of the problem domain, plant represent real-world elements, connections and flow-buses define the network architecture, and flow-bus amalgamation can provide a convenient modeling compromise. From the program domain, processes, commodity flows, flow balances, graphs, and the various algorithms provide useful modeling abstractions. Note that, in the first instance, the assumptions given apply to process descriptions as opposed to plant entities.

8.7. Plant specialization and demand and supply

The plant within *deeco* naturally divide into six specialist categories: demand (in the first instance, for exergy-service), conversion, transport, gateway (for import/export), storage, and sourcing (or collector). Space precludes a detailed description of these, but two plant categories warrant further comment. Model-wise, the demand plant provide the *rationale* for the system by 'translating' demand for exergy-service information into, as appropriate, upstream *fuel* requests. And the sourcing plant 'provide' *fuel* given that they are enabled in light of the prevailing environmental information and have been instructed to do so by the UCP. For example, a wind-turbine generator may only supply electricity when the interval-averaged ambient wind-speed v_0 maps to its power curve (alternatively, historical wind-farm output data can be used directly if more appropriate).

8.8. Cost creation and unit commitment

Unit commitment in *deeco* is based on either penalty minimization or, in the case of prescribed rules, penalty avoidance – hence cost creation procedures are required. Engineering-based cost creation can depend on one of the following notions: *fuel* flow, elapsed time, or plant existence – or restated in more conventional terms: duty, standing, and establishment costs, respectively. Non-engineering cost creation can derive from, for instance, *emissions permit* flow (a feature supported by *deeco* but not yet implemented by plant modules). Cost creation is the province of the CCE. One cost creation assumption is ubiquitous enough to be accorded its own entry, although, unlike some other lettered assumptions, this assumption is inspired by solver and performance considerations rather than being endemic to the basic framework.

Assumption B. Cost creation is linear with respect to associated flows when used as an UCP objective.

This assumption requires that the costs used by the UCP be linear on flow. Strictly speaking, this assumption applies directly to the process descriptions rather than their host plant, so that flow-convex costs can be approximated by placing several process linear descriptions in *parallel* in one plant. Non-UCP cost creation may be arbitrary in form, because these costs are simply tallied and reported.

As indicated earlier, a UCP comprises an optimization strategy, a nominated management objective, and any prescribed unit commitment rules as may be required. Furthermore, a new UCP objective may be created from a linear weighting of pre-existing UCP objectives. Each UCP has some associated real-world interpretation, which will need to be justified in terms of model purpose and on-the-ground context. The optimization solvers themselves also possess certain technical characteristics and corresponding algorithmic complexities.

The simplest UCP adopts an optimization strategy based solely on flow-linear cost creation – which, together with assumption C, is equivalent to duty-linear cost creation. The problem then reduces to a sequence of time-local minimum cost flow problems (MCFP) which can be solved successively using dedicated graph-theoretic algorithms [53] or recast by means of matrix algebra and passed to an LP solver [13]. This latter UCP strategy is used in the current release of *deeco*, but, in addition, the network problem is formulated such that storage plant are recharged whenever low-penalty supply is available [7,25]. In this case, the decision variables are the set of logically-recast commodity flows $\{\dot{F}^t\}$.

Financial costs are generated using the *annuity* method [5]. This method requires information concerning investment cost, salvage cost (possibly zero), economic life, discount rate, and perhaps asset age and valuation in order to determine a levelized *fixed* cost for each plant. Externality costs can also be estimated and included, as required by some forms of public interest analysis. *Fuel* costs and other flow-related costs are used to determine a horizon-averaged *variable* cost for each plant. These two cost categories can then be combined and summed over all plant to produce a levelized cost for the scenario. Plant which are being evaluated but which do not yet 'exist' may be sized on the basis of their maximum instructed duty. At present, only variable cost minimization is supported as a financial objective. However, plant which are clearly under-utilized can be *removed* and the analysis rerun – which can go some way toward addressing the full cost problem. On the other hand, existing energy system facilities are often operated so as to minimize operational costs, in which case the current UCP arrangement is quite appropriate.

8.9. The key deeco building blocks generalized

The central building block of *deeco* is the plant entity or, in programmatic terms, the plant module instance. Its general arrangement is shown in figure 4. The classification

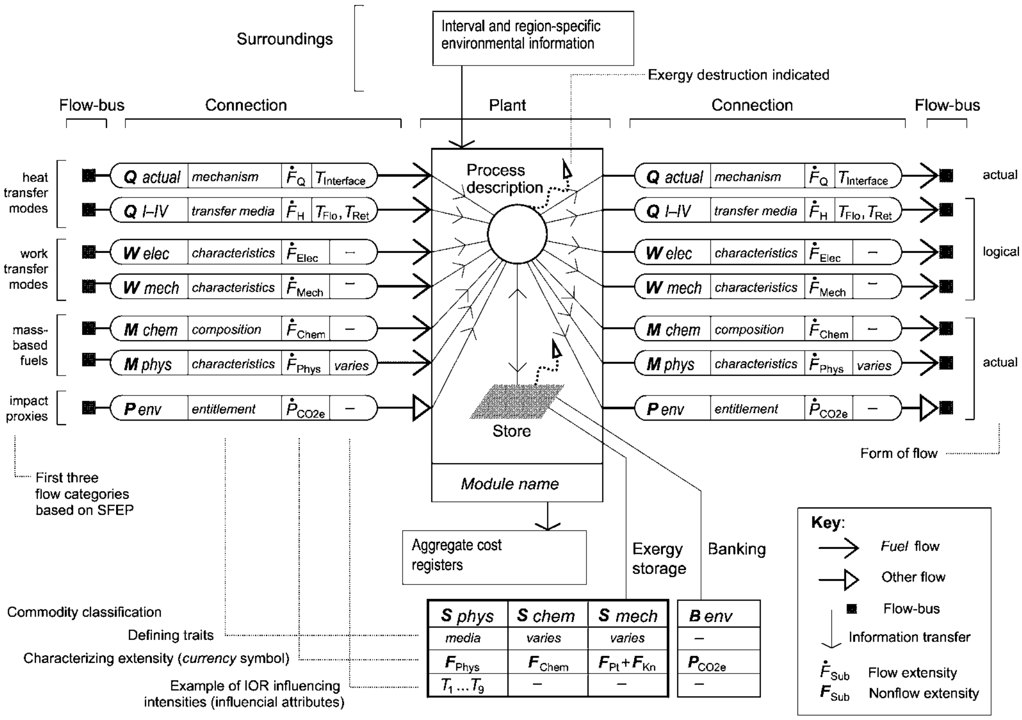

Figure 4. A generalized plant/connection/flow-bus. The classification of *fuel* connections arises directly from the SFEP concept. Multiple flows of each type are possible although indexing will be needed. Note the presence of non-engineering commodity types – for instance, environmental impact entitlements.

of connection and storage types aligns *directly* with that used in exergy analysis.

Plant provide a convenient way to contain more than one process description – which may be done for one of several reasons: stratified thermal storage can be modeled as a set of discrete, exergy-destructing processes (dropping the 'description' qualifier for convenience). Certain convex nonlinear behavior – for instance, quadratic losses in electricity transmission – can be captured by connecting several aphysical processes in parallel within one plant instance [43]. Coupled processes can share a multi-dimensional constraint space – for example, variable ratio cogeneration can use a 2-dimensional heat/power constraint polygon [8,48]. And real-word entities which are similar but spatially distinct can be aggregated to form a single plant instance, as appropriate – for example, one *meta*-house might represent an entire housing-stock type [25]. In these cases, the plant IOR is simply the collection of IOR from the contained processes plus any internal flow splitting and joining balances as may be needed. However, only those flow variables which lie *outside* of plant will be of interest in terms of model interpretation.

deeco also supports flows which are 'non-engineering' in the sense that they are not required for the technical operation of the plant. One such example is emissions permits, although other forms of priced and/or constrained resource use entitlement –

such as the use of natural rivers as heat sinks – could be amenable to inclusion. As far as *deeco* is concerned, non-engineering flows are no different from *fuel* flows in terms of treatment. Such commodities – which may be restricted in terms of scope – can, as appropriate, be: purchased and sold – analogous to import and export, stored for future use, and subject to UCP control in the same way as *fuel* flows.

8.10. Environmental parameters

Surrounding thermodynamic and economic conditions are given as an appropriate collection of time-series parameters – from which a set of interval-specific environmental data vectors $\{\mathbf{U}^t\}$ can be derived for use in IOR, CCE, and STE. Environmental parameters are often expressed as either continuous intensities or dimensionless binaries – for example: ambient air temperature T_0, solar insolation I_0, interval-averaged ambient wind speed v_0, cooling water availability $a_{\text{cw}} \in \{0, 1\}$, and wholesale electricity price p_{gxp}. These last three parameters can be given as a plant-specific time-series if this would be more appropriate. The environment may also be spatially subdivided by region (not supported in the current release of *deeco* but under development).

8.11. Plant behavior from a unit commitment procedure (UCP) perspective

From the perspective of a UCP, plant are characterized by their IOR and CCE. The following assumption is required to make the optimization problem tractable.

Assumption C. Plant input/output relationships (IOR) are linear with respect to their associated flows.

This assumption requires that the χ and ψ coefficients of plant input/output relationships (see equation (1)), once determined for a given time-interval, remain independent of the system extensities – or, equivalently, generalized plant efficiency, once set, remains independent of plant duty.

Like assumption A, this assumption is not as onerous as it might first seem. Plant which operate duty-cycle control at a higher frequency than the selected time-interval often broadly comply. As do power schemes that operate multiple units – for instance hydro-schemes with a number of generator-sets. Furthermore, assumption C only places a restriction on duty-dependence – IOR can be arbitrary in form with regard to $\mathbf{J}^t$, $\mathbf{S}^t$, $\mathbf{U}^t$, and t.

8.12. Influential attribute setting (IAS)

Influential attributes are those flow intensities which potentially have a *first-order influence* on the connected plant IOR. In many cases, connections of this type employ a recirculating working fluid. This means that, in the first instance, the interval-specific, connection-specific, influential attributes vector $\mathbf{J}^t$ would take the following general form:

$$\mathbf{J}^t = \left(\mathbf{J}^t_{\text{Flo}}, \mathbf{J}^t_{\text{Ret}}\right)^{\text{T}}, \quad \text{with } \mathbf{J}^t_{\{\text{Flo,Ret}\}} = \left(T^t, p^t, v^t, x^t, \ldots\right)^{\text{T}}, \tag{2}$$

where: 'Flo' and 'Ret' indicate the *flo* and *return* values, respectively, T is bulk temperature, p is bulk (static) pressure, and v is bulk velocity. In the case of two-phase condensing systems (wet steam), the phase ratio (dryness fraction) x would replace either T or p. The physical *flo* and *return* linkages will have earlier been abstracted as a single logical commodity flow.

The direct numerical determination of $\mathbf{J}^t$, system-wide, is a difficult task and lies well outside the possibilities (and spirit) of *deeco*. Instead, only those intensities that significantly influence IOR need to be captured and estimated. The setting of such variables within *deeco* relies on empirical considerations and two related IAS strategies can be adopted: the setting process can mimic the control systems and control hierarchies present in the real-world system. Or the setting process can replicate the analysis a design engineer would adopt when determining conditions in the same context. For example, the *deeco* space-heating module uses the second approach [8]. Influential attributes are resolved near the beginning of time-interval but prior to UCP optimization (refer to figure 5). The setting of influential attributes requires the following two assumptions.

Assumption D. Influential attribute setting (IAS) by a two-pass deterministic procedure is acceptable.

This assumption requires that the influential attributes can set in a two-pass deterministic procedure (given as algorithm 1).

Assumption E. Plant which communicate when influential attribute setting (IAS) cannot be connected cyclically in regard to their connections (encapsulated commodity flows).

This assumption is present to ensure that the procedure indicated in assumption D is tractable.

The two-pass deterministic procedure is outlined in algorithm 1 and can be thought of operating on the principal *deeco* diagraph – although in practice the algorithm acts directly on the plant traversal list. The vertex ordering routine is not described here but details can be found in [58, p. 53]. Algorithm 1 identifies a set of spanning out-trees, each of which covers groups of plant who communicate about the setting of influential attributes. These out-trees are sometimes called *thermal sub-networks* (TSN) because IAS is invariably associated with heat transport in the present version of *deeco*. Assumption D also implies further limitations when dealing with flows which branch and/or join though amalgamated flow-buses. Space precludes a detailed description but four types of attribute passing configuration can be identified, labeled I–IV. Details of these types and of the implemented IAS procedure for specific plant can be found in [8]. Assumptions D and E also limit the amount of detail in terms of engineering structure that can be included in a *deeco* model.

Algorithm 1. The influential attributes setting (IAS) algorithm.
Input: A directed bipartite acyclic graph $G = (V, E)$ with each vertex $\in V$ labeled $1, \ldots, j, \ldots, g$ such that $j < j'$ for each (tail to head) edge $\in E$ given by (j, j').
Output: None – the algorithm is used for its side-effects.

```
// the first pass is an upstream traversal
f := g;   // f is the current vertex label
while f > 1
  if f represents a plant instance    // as opposed to a flow-bus instance
    foreach flow ∈ {entering flows} ∩ {attribute carrying flows}
              set those performance-influencing flow attributes, if any, which can be
                 resolved because the plant instance has sufficient information;
              forward these attributes via the flow connection under consideration to
                 all adjoining (upstream) plant;
  f −−;
// the second pass is a downstream traversal
while f < g
  if f represents a plant instance
    foreach flow ∈ {exiting flows} ∩ {attribute carrying flows}
              set any remaining performance-influencing flow attributes, using
                 attributes set earlier as the case may be;
              forward these attributes via the flow connection under consideration to
                 all adjoining (downstream) plant;
  f++;
```

8.13. Modeler jurisdiction and abutting networks

The issue of jurisdiction arises because, in general, the model user (on behalf of their client or their public) has influence – be it direct or referred – over only *part* of the system. *deeco* deals with this issue by restricting the UCP to *this* domain and by representing abutting networks by single specialist gateway plant through which all import/export activities are conducted. The orthogonality assumption A applies equally to these gateway plant, which means that selected transfer rates should have *nil* effect on associated flow intensities, including *fuel* price. Notwithstanding, *fuel* tariffs with a convex *banded* structure can be modeled using aphysical disaggregation – which allows common forms of electricity supply contract to be captured. The notions of model scope and modeler authority gives rise to the concept of *distributed planning*.

8.14. End-of-horizon issues

Assumption F. End-of-time-horizon boundary conditions – including storage inventories – are to be met.

The main use of assumption F at present is to ensure that nominated closing storage inventories are honored. *deeco* currently achieves this through complete horizon iteration – a method which can impose a substantial computational overhead.

8.15. Plant lifecycle

Figure 5 shows the lifecycle of a plant within *deeco* in terms of the current implementation.

9. UCP optimization strategies

This section provides a brief review of the optimization strategies that can be used to inform UCP. Optimization can operate at both time-local and inter-temporal levels.

The time-local problem involves determining an optimal flow routing set – which is equivalent to determining an optimal unit commitment set. This component of *deeco* is currently structured as a time-local linear program (LP) solved with a modified version of the simplex algorithm from Numerical Recipes [47]. The actual LP problem has been formulated in a particular way to ensure that storage recharge opportunities are included as part of the solution. This *recursive dynamic optimization* scheme, adapted for inter-temporal optimization, solves a sequence of time-local problems nested in an overarching simulation of the plant evolution – this evolution can be especially significant when storage is involved. Work is underway to re-implement the time-local optimization routine as a mixed-integer linear program (MILP), which will allow certain important plant commitment procedures to be supported directly, including stand-by shut-down. This exercise will also create new classes of decision variable.

Inter-temporal optimization concerns issues such as use-of-storage, use-of-entitlements, and conversion plant ramp-rates – the latter may well be significant in the case of high-temperature fuel-cell technologies, for example. If forecast information of perfect or limited certainty is available, then these across-time issues may be amenable to explicit inter-temporal optimization. The most direct strategy is to nest the time-local problem within a dynamic program (DP) structure [7]. Proof-of-concept trials, coded in C++ [36,37] and MATLAB, have been completed using a time-global nested DP/LP formulation. As long as limitations arising from unfavorable time complexity ("the curse of dimensionality") are taken into account, particularly in relation to storage utilization, the use of nested DP formulations should provide useful additional functionality.

10. Interpretation using CO_2-e abatement supply as an example

This section takes a short look at model interpretation issues. Policy support models must provide decision-makers with readily assessed information – which implies that the information be: option-based, policy-target-oriented, and of low dimensionality. *deeco* results can be presented on *trade-off diagrams* whereby the results from several scenario

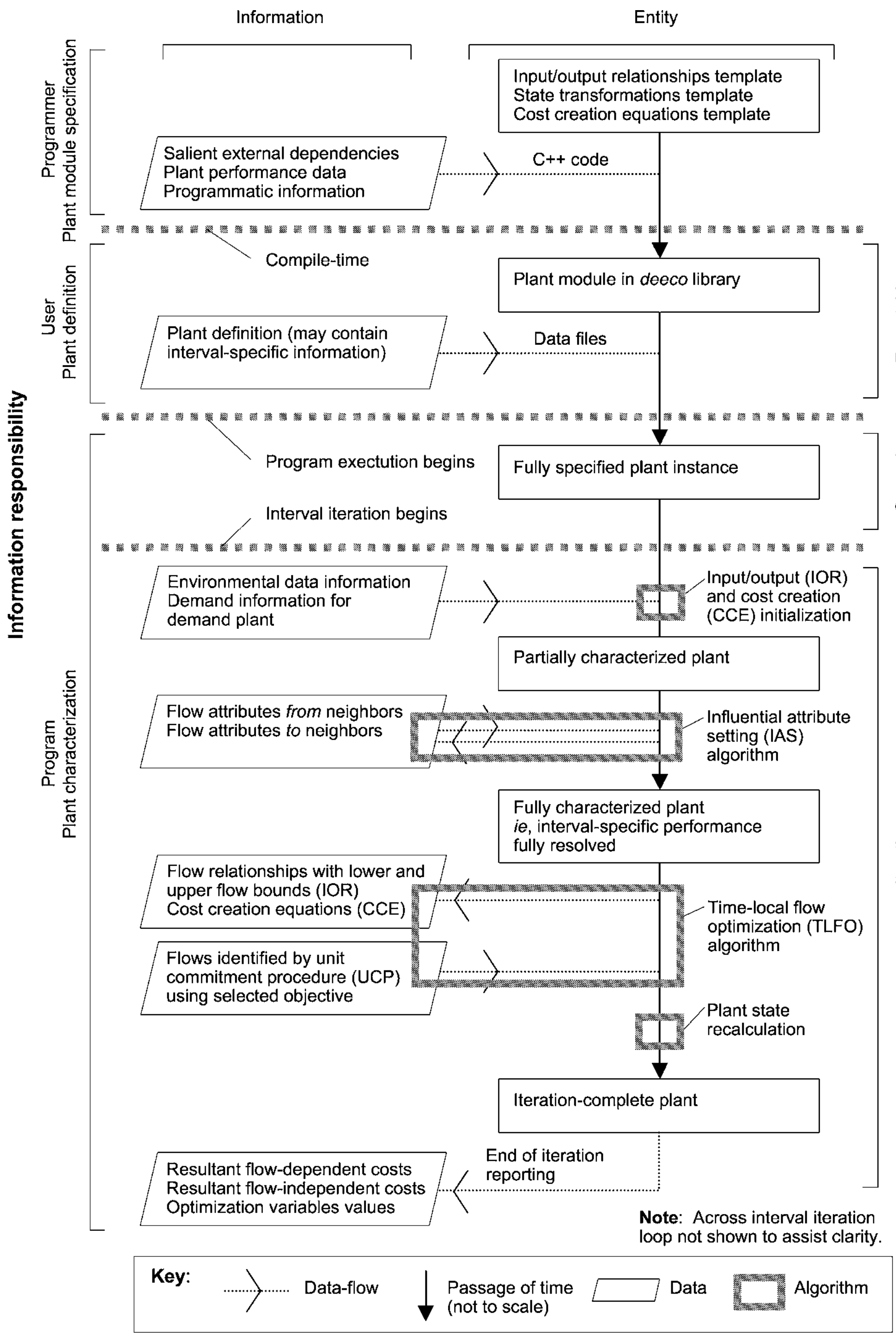

Figure 5. The lifecycle of a plant as per the current release of *deeco* – from the perspective of that plant. This diagram also indicates the staging of key procedures during any given time-interval and thereby depicts the temporal relationships between many of the ideas presented in section 8. *Source*: [43, figure 8.6].

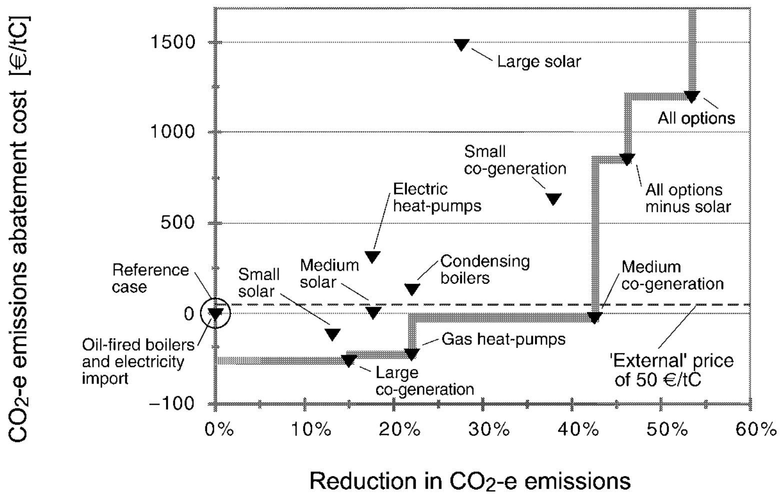

Figure 6. A typical *deeco* trade-off diagram, adapted from the Würzburg study. A so-called trade-off line has been added in gray – normally, only those options which fall on the lower right corners need further consideration. Negative costs represent a "win–win" situation, a result which emphasizes the fact that *deeco* analysis is situation-specific and that conclusions cannot be automatically transferred elsewhere. An arbitrary 'external' CO_2-e abatement price of €50/tC is shown as a dashed line for comparison – this cost was not included in the original investigation. The reference case emissions were 1.03 MtC/year. See [9, table 2] for further details. *Source*: [7, figure 3.5].[18]

runs are plotted on one figure. Each projected policy outcome is shown in terms of its sustainability cost category decrease (x-axis) *versus* its levelized financial cost increase (y-axis) – which may be negative. Figure 6 shows a variant of this type of diagram, as generated by the Würzburg study [9]. The sustainability improvement is reported in terms of mitigated or avoided CO_2-e – which is topical in light of the Kyoto Protocol. A line representing the 'external' price for *carbon* abatement, as might be set by emissions trading, has been added – only options falling below this line should be adopted, in the absence of further non-monetarized co-benefits.

11. Summary

The modeling environment presented is primarily applicable to energy system problems involving: (1) *correlation effects* between supply opportunity and demand for exergy-service, (2) *dynamic effects* associated with use-of-storage and import/export, and (3) *network effects* due to losses and constraints within the system under investigation. The model can be used to analyze multiple systems modifications, including those staged over time, and supports: (1) *physical system* change, (2) *use-of-system* change, and (3) *unit commitment procedure* change. The model can also take into account certain flow attributes which have a direct influence on plant operating efficiencies and/or

[18] The unit 'tC' is *tonnes carbon* equivalent: 1 tC is equal to 3.66 tCO_2-e.

capacities. The model was cast in this paper in a public policy support role, but can also be applied to single-operator scheme design and multiple-participant private policy formulation.

The specification of demand in terms of service wherever practicable is important because this allows demander motivations to be captured first-hand and means that energetically-passive techniques can be investigated on an equal footing *vis-à-vis* active techniques.

The model is well suited to the analysis of distributed solutions, as these tend to be sensitive to effects listed above. Experience indicates that sets of distributed solutions can collectively reinforce or undermine one other. *deeco*-type modeling is able to identify these interactions and assist with the search for synergies. One interesting distributed solution variant is that of modifying unit commitment procedures in order to provoke cost-effective sustainability outcomes. This form of cooperative emergent benefit may represent a considerable yet under-recognized resource in the context of climate change mitigation. Likewise, the degree to which detrimental system integration hinders the uptake of dispersed solutions remains an open question, but is also one that *deeco*-type modeling could help answer.

The model provides a unifying view of the *sustainable energy* problem and shifts the focus from second-tier strategies, such as renewable energy uptake and energy efficiency improvement, to first-tier policy objectives, namely reduced greenhouse gas emissions and reduced depletable resource dependency.

Acknowledgments

Robbie Morrison acknowledges support from New Zealand Government Bright Future Top-Achiever Doctoral Scholarship TAD 523.

References

[1] R. Ayres, The minimum complexity of endogenous growth models: the role of physical resource flows, Energy – The International Journal 26(9) (2001) 817–838.

[2] H.D. Baehr, *Thermodynamik: Grundlagen und technische Anwendungen*, 10 Auflage (Springer, Berlin, 2000). (Translation: *Thermodynamics: Fundamentals and Technical Applications*, 10th edition.)

[3] D. Beck, J. Paetzold and J. Nilges, Dezentrale Energiesysteme in elektrischen Verteilungsnetzen, Brennstoff–Wärme–Kraft 53 (2001) 63–66. (Translation: Distributed energy systems in electricity distribution grids.)

[4] A. Bejan, *Advanced Engineering Thermodynamics*, 2nd ed. (Wiley, New York, 1997).

[5] A. Bejan, G. Tsatsaronis and M. Moran, *Thermal Design and Optimization* (Wiley, New York, 1996).

[6] T. Bruckner, Solarthermie und rationelle Engergieverwendung, Diplomarbeit, Institut für Theoretische Physik, Universität Würzburg, Germany (1992). (Translation: Solar thermal energy and energy efficiency improvement, Master Thesis.)

[7] T. Bruckner, Dynamische Energie- und Emissionsoptimierung regionaler Energiesysteme, Doktorarbeit, Institut für Theoretische Physik, Universität Würzburg, Germany (1997). (Translation: Dynamic energy and emissions optimization for regional energy systems, Ph.D. Thesis.)

[8] T. Bruckner, Benutzerhandbuch *deeco*, Version 1.0, Institut für Energietechnik, Technische Universität Berlin, Germany (2001). (Translation: User's Handbook for *deeco*.)

[9] T. Bruckner, H.-M. Groscurth and R. Kümmel, Competition and synergy between energy technologies in municipal energy systems, Energy – The International Journal 22(10) (1997) 1005–1014.

[10] J. Bruhn, Regenerative Energiequellen und Verfahren der rationellen Energieverwendung: Synergie und Konkurrenz, Diplomarbeit, Institut für Energietechnik, Technische Universität Berlin, Germany (2000). (Translation: Renewable energy sources and energy efficiency: synergy and counteraction, Master Thesis.)

[11] D.W. Bunn and E.R. Larsen (eds.), *Systems Modelling for Energy Policy* (Wiley, Chichester, 1997).

[12] A.C.B. den Ouden, PRODESign: a program for optimisation and dimensioning of energy conversion systems, in: *Proceedings of ECOS 2000: The International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Aspects of Energy and Process Systems*, University of Twente, Enschede, The Netherlands, 05–07 July 2000, Part 3, ed. G.G. Hirs (2000) pp. 1691–1703.

[13] U. Derigs, *Programming in Networks and Graphs: On the Combinatorial Background and Near-Equivalence of Network Flow and Matching Algorithms* (Springer, Berlin, 1988).

[14] M.A. Ellis and B. Stroustrup, *The Annotated C++ Reference Manual* (Addison-Wesley, Reading, MA, 1992), reprinted with corrections, October 1992.

[15] Energy Efficiency and Conservation Authority, National Energy Efficiency and Conservation Strategy (Energy Efficiency and Conservation Authority, Wellington, New Zealand, September, 2001).

[16] European Commission, Energy for the future: renewable sources of energy, White Paper for a Community Strategy and Action Plan, COM(97), 599 final (26 November 1997).

[17] European Commission, Communication from the Commission on the implementation of the first phase of the European Climate Change Programme, COM(2001), 580, European Commission, Brussels (23 November 2001).

[18] European Commission, Towards a European strategy for the security of energy supply, Green Paper, Office for Official Publications of the European Communities, Luxembourg (2001).

[19] European Commission, Community research: energy, environment and sustainable development, Integration of Renewable Energy Sources and Distributed Generation in Energy Supply Systems, Office for Official Publications of the European Communities, Luxembourg (2001).

[20] A.M. Gibbons, *Algorithmic Graph Theory* (Cambridge University Press, Cambridge, 1985).

[21] G.A. Goldstein and L.A. Greening, Energy planning and the development of carbon mitigation strategies – using the MARKAL family of models, International Resources Group, Washington, DC (April 2001), updated.

[22] P.E. Grohnheit, Application and limitations of annual models for electricity capacity development, in: *Systems Modelling for Energy Policy*, eds. D.W. Bunn and E.R. Larsen, chapter 7 (Wiley, Chichester, 1997) pp. 89–116.

[23] H.-M. Groscurth, *Rationelle Energieverwendung durch Wärmerückgewinnung*, Doktorarbeit, (Physica-Verlag, Heidelberg, 1991). (Translation: *Energy Efficiency Improvement through Heat Recovery*, Ph.D. Thesis.)

[24] H.-M. Groscurth, T. Bruckner and R. Kümmel, Energy, cost, and carbon dioxide optimization of disaggregated, regional energy-supply systems, Energy – The International Journal 18(12) (1993) 1187–1205.

[25] H.-M. Groscurth, T. Bruckner and R. Kümmel, Modeling of energy-services supply systems, Energy – The International Journal 20(9) (1995) 941–958.

[26] H.-M. Groscurth and K.-P. Kress, Fuzzy data compression for energy optimization models, Energy – The International Journal 23(1) (1998) 1–9.

[27] H.-M. Groscurth, R. Kümmel and W. van Gool, Thermodynamic limits to energy optimization, Energy – The International Journal 14(5) (1989) 241–258.

[28] D. Henning, MODEST: an energy-system optimisation model applicable to local utilities and countries, Energy – The International Journal 22(12) (1997) 1135–1150.

[29] D. Henning, Cost minimization for a local utility through CHP, heat storage and load management, International Journal of Energy Research 22(8) (1998) 691–713.

[30] R. Jank (ed.), *A Guidebook for Advanced Local Energy Planning (ALEP)* (International Energy Agency, Paris, 2000).

[31] M. Kainuma, Y. Matsuoka and T. Morita, CO_2 emission forecast in Japan by AIM/end-use model, OPSEARCH 38(1) (2001) 109–125.

[32] M. Kainuma, Y. Matsuoka, T. Morita and G. Hibino, Development of an end-use model for analysing policy options to reduce greenhouse gas emissions, IEEE Transactions on Systems, Man, and Cybernetics, Part C, Applications and Reviews 29(3) (1999) 317–324.

[33] A. Karlqvist, Network as dynamic systems, in: *Networks in Action: Communication, Economics and Human Knowledge*, eds. D. Batten, J.L. Casti and R. Thord (Springer, Berlin, 1995) pp. 82–106.

[34] T.J. Kotas, *The Exergy Method of Thermal Plant Analysis* (Krieger, Malabar, FL, 1995), reprinted with corrections and new appendix G.

[35] R. Kühner, Ein erweiterter prozeßtechnischer Modellbildungsansatz für die energiewirtschaftliche Planung, in: *Operations Research Proceedings 1996: Selected Papers of the Symposium on Operations Research*, Braunschweig, Germany, 03–06 September 1996, eds. U. Derigs et al. (Springer, Berlin, 1996). (Translation: An extended energy process modeling framework for use in energy planning.)

[36] A. Kunkel, Dynamische Optimierung eines Energieversorgungssystems mit Wärmespeicher, Diplomarbeit, Institut für Theoretische Physik, Universität Würzburg, Germany (1994). (Translation: Dynamic optimization of an energy supply system containing thermal storage, Master Thesis.)

[37] A. Kunkel, H. Schwab, T. Buckner and R. Kümmel, Kraft–Wärme–Kopplung und innovative Energiespeicherkonzepte, Brennstoff–Wärme–Kraft 48 (1996) 54–60. (Translation: Cogeneration and innovative energy storage concepts.)

[38] J. Lermit and N. Jolands, *Monitoring Energy Efficiency Performance in New Zealand: A Conceptual and Methodological Framework* (Energy Efficiency and Conservation Authority, Wellington, New Zealand, September 2001).

[39] D. Lindenberger, T. Bruckner, H. Groscurth and R. Kümmel, Optimization of Solar district heating systems: seasonal storage, heat pumps, and cogeneration, Energy – The International Journal 25(7) (2000) 591–608.

[40] D. Lindenberger, T. Bruckner, H. Groscurth and R. Kümmel, Heat, electricity, sun, and fossil fuels: dynamic energy, emission, and cost optimisation, High Temperatures – High Pressures 33 (2001) 463–468.

[41] D. Lindenberger and R. Kümmel, Modernization of regional energy systems, in: *Proceedings of the 2nd International Workshop: Advances in Energy Studies: Exploring Supplies, Constraints, and Strategies*, Porto Venere, Italy, eds. S. Ulgiati et al. (23–27 May 2000) pp. 85–93.

[42] S. Messner, A. Golodnikov and A. Gritsevskii, A stochastic version of the dynamic linear programming model MESSAGE III, Energy – The International Journal 21(9) (1996) 775–784.

[43] R. Morrison, Optimizing exergy-services supply networks for sustainability, M.Sc. Thesis, Physics Department, University of Otago, New Zealand (2000).

[44] R. Morrison and T. Bruckner, High-resolution modeling of distributed resources using *deeco*: adverse interactions and potential policy conflicts, in: *Proceedings of the 3rd International Workshop: Advances in Energy Studies: Reconsidering the Importance of Energy*, Porto Venere, Italy, 24–28 September 2002, eds. S. Ulgiati et al., in press.

[45] G.L. Nemhauser and L. A. Wolsey, *Integer and Combinatorial Optimization* (Wiley, New York, 1988).

[46] E. Nieuwlaar, Enerpack 5: a package for the thermodynamic analysis of energy systems, 5th ed., Report No. 96057/Software, Department of Science, Technology, and Society, Utrecht University, Utrecht (13 August, 1996).

[47] W.H. Press, S.A. Teukolsky, W.T. Vetterling and B.P. Flannery, *Numerical Recipes in C: The Art of Scientific Computing*, 2nd ed. (Cambridge University Press, Cambridge, 1992).

[48] K. Ramsel, CO_2- und Kostenoptimierung mit *deeco*: Modellierung des emissionsoptimierten Einsatzes von Gas- und Dampfturbinen-Anlagen, Diplomarbeit, Institut für Energietechnik, Technische Universität Berlin, Germany (2002). (Translation: CO_2 and monetary cost optimization with *deeco*: modeling of emissions-optimal unit commitment for gas and steam turbine plant, Master Thesis.)

[49] U. Remme, G.A. Goldstein, U. Schellmann and C. Schlenzig, MESAP/TIMES – advanced decision support for energy and environmental planning, in: *Operations Research Proceedings 2001 – Selected Papers of the International Conference on Operations Research (OR 2001)*, 03–05 September 2001, Duisburg, Germany, eds. P. Chamoni, R. Leisten, A. Martin, J. Minnemann and H. Stadtler (2002) pp. 59–66.

[50] M.A. Salman, Concepts of power system modeling and simulation, in: *Systems Modeling and Computer Simulation*, ed. N.A. Kheir, 2nd ed., chapter 15 (Marcel Dekker, New York, 1996) pp. 625–656.

[51] H. Schwab, Dynamische Optimierung von regionalen Energieversorgungssystemen unter Einbeziehung von (supraleitenden) Energiespeichern, Diplomarbeit, Institut für Theoretische Physik, Universität Würzburg, Germany (1994). (Translation: Dynamic optimization of regional energy supply systems taking into account (superconducting) energy storage, Master Thesis.)

[52] A.J. Seebregts, G.A. Goldstein and K.E.L. Smekens, Energy/environmental modeling with the MARKAL family of models, in: *Operations Research Proceedings 2001 – Selected Papers of the International Conference on Operations Research (OR 2001)*, 03–05 September 2001, Duisburg, Germany, eds. P. Chamoni, R. Leisten, A. Martin, J. Minnemann and H. Stadtler (2002) pp. 75–82.

[53] D.K. Smith, *Network Optimisation Practice: A Computational Guide* (Ellis Horwood, Chichester, 1982).

[54] C. Soanes, A. Spooner and S. Hawker (eds.), *Oxford Paperback Dictionary, Thesaurus, and Wordpower Guide* (Oxford University Press, Oxford, 2001).

[55] G. Sundberg and D. Henning, Investments in combined heat and power plants: influence of fuel price on cost minimized operation, Energy Conversion and Management 43(5) (2002) 639–650.

[56] G. Sundberg and B.G. Karlsson, Interaction effects in optimising a municipal energy system, Energy – The International Journal 25(9) (2000) 877–891.

[57] W. van Gool, The value of energy carriers, Energy – The International Journal 12 (1987) 509–518.

[58] H. Walther and G. Nägler, *Graphen, Algorithmen, Programme* (Springer, Wien, 1987). (Translation: *Graphs, Algorithms, Programs*.)

[59] T.C. Weitzen, The C++ graph classes: a tutorial, in: *Standard Components*, Release 3.0, *Programmers Guide*, AT&T & UNIX Systems Laboratories, 7/1–7/30 (1992). (Part of the Hewlett-Packard HP-UX workstation documentation.)

[60] R. Yokoyama, Y. Hasegawa and K. Ito, A MILP decomposition approach to large scale optimization in structural design of energy supply systems, Energy Conversion and Management 43(6) (2002) 771–790.