Working Paper

Energy-Economy Analysis: Linking the Macroeconomic and Systems-Engineering Approaches

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WP-95-42
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Abstract

A necessary condition for an internally controlled soft-linking of two models, is a common, formalised language describing the areas of overlap between the models. This principle is discussed and demonstrated for the softlinking of the macroeconomic and systems-engineering models in the scenario work of the Environmentally Compatible Energy Strategies (ECS) Project at IIASA. The Reference Energy System (RES) can describe how the models identify their relevant systems in the overlapping areas. Using RES as the common language, a Clearing House is set up to develop the soft-linking procedures and to control the quality of the linking. The procedures permit an interpretation of a key parameter describing energy efficiency improvements in the macroeconomic model into results obtained by the systems-engineering model. Other insights emerge into the "top-down versus bottom-up approaches", which is a label sometimes used to describe the two alternative modelling perspectives. It is illustrative to discuss the insights in terms of fallacies that may result from a reliance on one single perspective. We identify here the "reductionist" and the "black box" fallacies.

1. Introduction

Understanding the energy-economy linkages is crucial for designing energy systems compatible with sustainable economic growth. Different perspectives are giving divergent views of these linkages and their consequences, so means for negotiating and integrating between different approaches are needed. The greenhouse gas debate provides an illustration. A central question concerns the development of energy systems compatible both with economic growth and management of the risk for climate change.

Much of the debate focus on the links among economic growth, the level of energy demands, the development of the energy system to supply these demands, and the technology and resource basis to support the energy system. Examples of how the links are treated are found in Nordhaus (1992), Jorgensen and Wilcoxen (1993), Manne and Richels (1992), Kram *et al.* (1992), Manne and Wene (1992). The debate is often connected with alternative analytical approaches. The approaches distinguish themselves by their design and use of various models and by their emphasis on technological data-bases. The alternative philosophies may be labeled "top-down macroeconomic" and "bottom-up engineering". The two approaches tend to disagree on the effects of energy efficiency improvements on future levels of energy demands, e.g., Manne and Richels (1990) and Williams (1990). The macroeconomic approach usually finds less effects on compounded future energy demands than the systems-engineering approach. Some authors refer to this disagreement as "the gap" (Wilson and Swisher, 1993). An interesting question is, whether it is possible to identify the cause of the disagreement as either different interpretations and uses of data, or differences in methodology and modelling tools.

The two approaches differ considerably in their identification of the relevant system.

The bottom-up, or systems-engineering, approach builds on detailed analysis of technological options and potentials for technical changes in the energy system. The models focus on energy flows. With the more sophisticated systems-engineering models, the complex network of resources, technologies and final users can be mapped to the desired scope and detail. Alternative energy pathways can be explored from extraction to final use. Such models are ideal tools for investigating fundamental technological changes in the energy system, including the consequences for emissions, investments and cash flows. Development of systems-engineering models started in the 1970s. Examples of such models for the whole energy system are found in Fishbone and Abilock (1981), van der Voort *et al.*(1984), Messner (1984) and Hake *et al.* (1994).

In the top-down, or macroeconomic, approach energy enters as a production factor. The interplay with other production factors to create economic growth is captured in production functions. The technical energy system is usually treated as a black box characterised by transfer functions where elasticities enter as parameters. The transfer functions show how price changes trigger fuel switches or alter the relation between the use of energy and other production factors ("energy conservation"), but the technologies responsible for these changes are not identified, e.g., Edmonds and Reilly (1985) and Nordhaus (1994). One exception is Manne (1978) and Manne and Richels (1992), where generic technologies for production of electricity and synthetic fuel are recognised. Productivity improvements are usually specified by external parameters, but have been endogenised in the Jorgensen and Wilcoxen (1993) general equilibrium model.

The macroeconomic models thus captures the feedbacks between the energy system and the rest of the economy; they address the effects of changing prices on economic activity, including the possible reallocation of resources that affect capital formation and economic growth. But the macroeconomic models have one more important function. They help to avoid the *reductionist fallacy*, e.g., the belief that the components in the compounded energy demand will remain the same in the future. Conversely, we note that the systems-engineering models help to avoid another fallacy. This can be called the *black box fallacy*, e.g., the belief that observation of previous inputs to and outputs from the energy system exhausts the possible responses, i.e., the possible internal states, of the system.

Fundamental technological changes in the energy system may involve considerable feedbacks to the rest of the economy. Conversely, the evaluation of economic instruments to control the risk of climate change needs to consider the technological response in the energy system. Linking a macroeconomic model and a systems engineering model will provide a tool for the required joint energy-economy analysis. It should also help to avoid both the reductionist and the black box fallacies. For the linking it is possible to use already peer-reviewed models, which avoids repeating earlier work and gives an initial quality to the efforts.

The first example of a linked models were reported by Hoffman and Jorgensen (1977). They linked the Brookhaven Energy System Optimisation Model (BESOM, Cherniavsky, 1974) with a general equilibrium model (Hudson and Jorgensen, 1974). Later efforts by the same group involved linking to a large input-output model (Groncki and Marcuse, 1979). During the 1980's, investigations using linked economic and system engineering models are reported by Berger *et al.* (1987) and by Yasukawa *et al.* (1989). In all these studies, the links between the models are of an informal nature, i.e., the information transfer between the models is directly controlled by the user. The first example of a formal linking of a macroeconomic and a systems-engineering model is reported by Manne and Wene (1992). The resulting energy-economy model is used for studies of national energy systems (Hamilton *et al.*, 1992, Niklasson *et al.*, 1995).

The purpose for the model linking is to provide an integrated energy-economy modelling framework for the Scenario work at the International Institute for Applied Systems Analysis (IIASA) (Nakicenovic *et al*, 1995). The project involves systems analysis of global energy perspectives, in order to identify potential environmental impacts, and mitigation and adaptation strategies. The time horizon is 2100, and the world is disaggregated into 11 regions.

A number of formal models are used to achieve consistency of the qualitative analysis. This paper reports on the informal linking ("softlinking") of a *macroeconomic* and a *systems-engineering* model. This energy-economy linking is at the core of the modelling efforts. The focus is on the long-term global energy development and associated greenhouse gas emissions. The effects of improved energy efficiency on the future levels of energy demands and the links to economic activity is crucial in assessing and managing the risk for climate change.

The model linking has provided insights into the top-down, bottom-up controversy discussed above. These insights are reported below. To substantiate these insights quite precise soft-linking procedures have to be implemented. The first part of the paper therefore develops a methodological basis for such procedures.

For the linking we choose two models that have proven track records both in global and environmental analysis. The bottom-up or systems-engineering model is MESSAGE III (Messner, 1984). The MESSAGE family of models has been used for the past two decades in analyses of national, regional and global energy systems. The latest adaptation of the ETA-MACRO model (Manne, 1978) is selected for the top-down macroeconomic analysis. Both models have roots in work done at IIASA in the mid-1970s. A more recent modification of ETA-MACRO is known as Global 2100

(Manne and Richels, 1992). Our adaptation of Global 2100 is referred to as 11R, to reflect its applicability to the 11 regions of this study.

The basis for controlled soft-linking is discussed in the following section. We describe the two models in a common language, the Reference Energy System (RES). The purpose is to identify where the two models overlap. An overlap is necessary for a feedback controlled soft-linking. Section 3 discusses the pros and cons of formal and informal linking ("hardlinking" and "softlinking"). It introduces the concept of Clearing House, which has the double role of generating insights and providing quality control for the informal linking. The relations between scenario generation and model linking is discussed in Section 4. Section 5 illustrates the linking for one of the 11 scenario regions. The results provide a comparison, in quantitative terms, of the treatment of energy efficiency improvements in the two models.

2. Identifying the Relevant System: The Reference Energy System in 11R and MESSAGE III

2.1. Description of the models in a common language

In the Introduction, we discussed how the macroeconomic and systems-engineering approaches differ in their identification of the relevant system. But the preview also indicated areas where the identified systems overlap. In fact, the root of the top-down, bottom-up controversy is the claim of the modellers for such overlaps. For consistency, the softlinking between the models representing the two approaches therefore has to be *internally* controlled, e.g., through iterations with feedback of information between the models. This means, that it must be possible to compare model results within the overlapping areas and then decide whether the models are describing the same phenomena and the same future. The procedures for feedback and comparison we will call *soft-linking procedures*. A necessary first step to develop such procedures is to describe the system identification made by the two models in a *common, formalised language*[1)].

For a controllable softlinking, the common language should provide common, unambiguous measuring points where the two models should yield identical results, e.g., for energy flows. This places a strong requirement on the language: if the results from the two models at the common measuring points differ by more than a pre-set value, it follows from the rules of the language that the models are not linked. The language is thus the basis for quality control of the softlinking. It also should guide the development of the softlinking procedures and help explain the differences due to different model approaches (the top-down bottom-up controversy).

There is no language that can both provide the measuring points and exhaustively describe the two models. We therefore have to settle for a minimum demand. The language should provide a full description of at least one of the models and substantial parts of the other. With these requirements it should be possible to decide either on common measuring points or that there is no overlap and therefore the prerequisite for an internally controlled softlinking does not exist. The systems engineering provide a suitable language, the Reference Energy System (RES).

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1 Language is here used in the sense of "means to communicate", cf language games (Wittgenstein, 1953). A language A is defined as "The total set of all understood language acts referring to language A". Example of a language act is when a professor gives a student a half-finished RES asking the student to enter Integrated Coal Gasification Combined Cycle power plant into the RES. If both agree that the student has done this correctly the language act is understood. The language act also belongs to the total set of language acts that defines language RES.

Figures 1 and 2 show the Reference Energy System (RES) in 11R and MESSAGE III. RES (Marcuse *et al.*, 1976) is a nested flow diagram. Horizontal lines indicate energy flows, and vertical lines indicate distribution systems or markets for energy carriers. In most cases an energy flow goes through an energy conversion technology, where the energy is transferred to one or more new energy carriers. In *Figure 1*, the energy conversion technology is indicated by a box. For practical reasons, the conversion technologies in *Figure 2* are indicated only by text strings. For the selected level of aggregation, the RES diagram shows all possible paths a unit of energy can take from primary energy to consumer.

RES can be used to give a fairly complete description of both the *scope* and the technological *detail* of a systems engineering model such as MESSAGE III (cf. Wene, 1989). Scope here indicates the boundaries of the system and the amount of optional technologies and alternative energy paths included in the model. The technological detail refers to the level of aggregation.

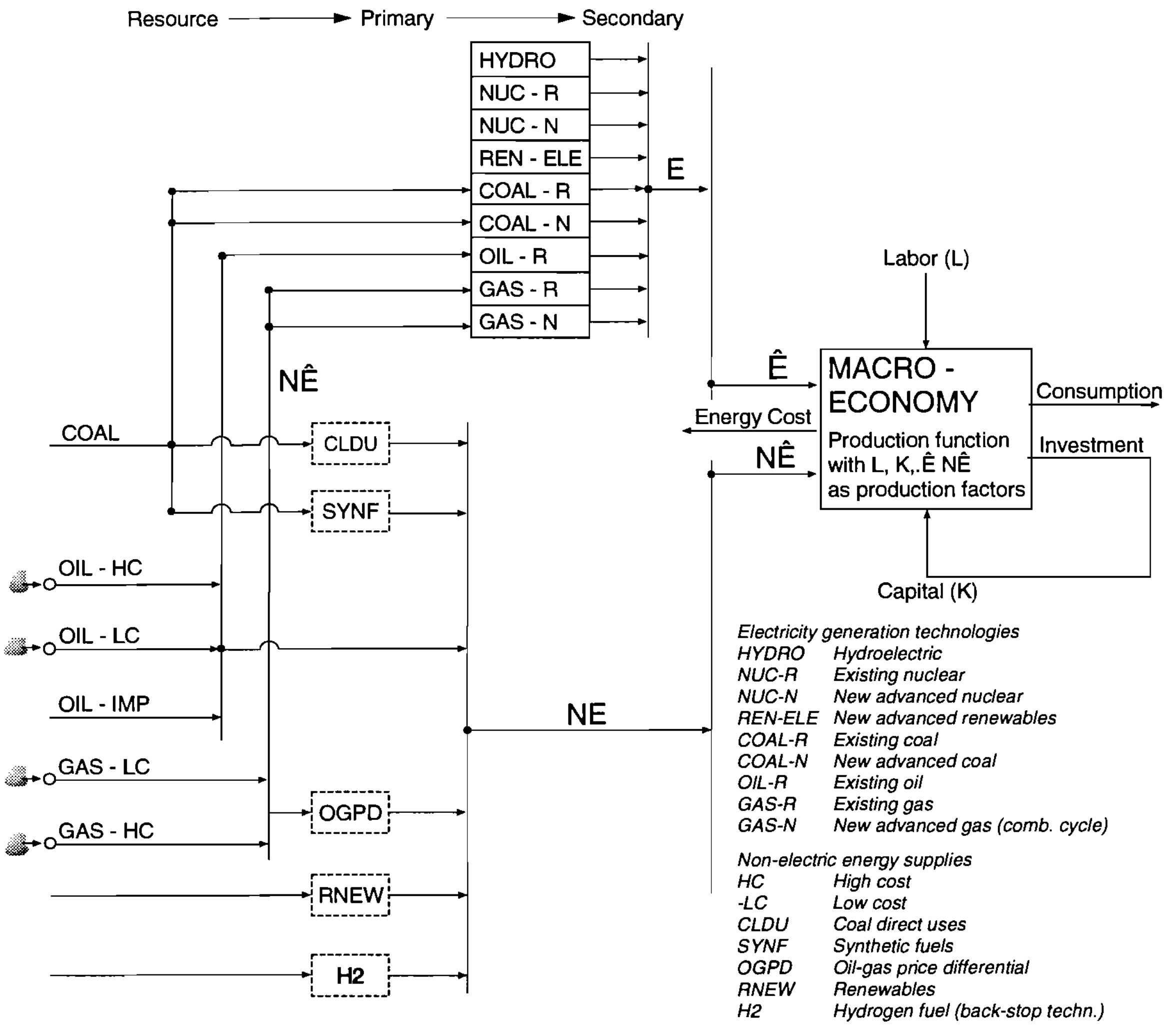
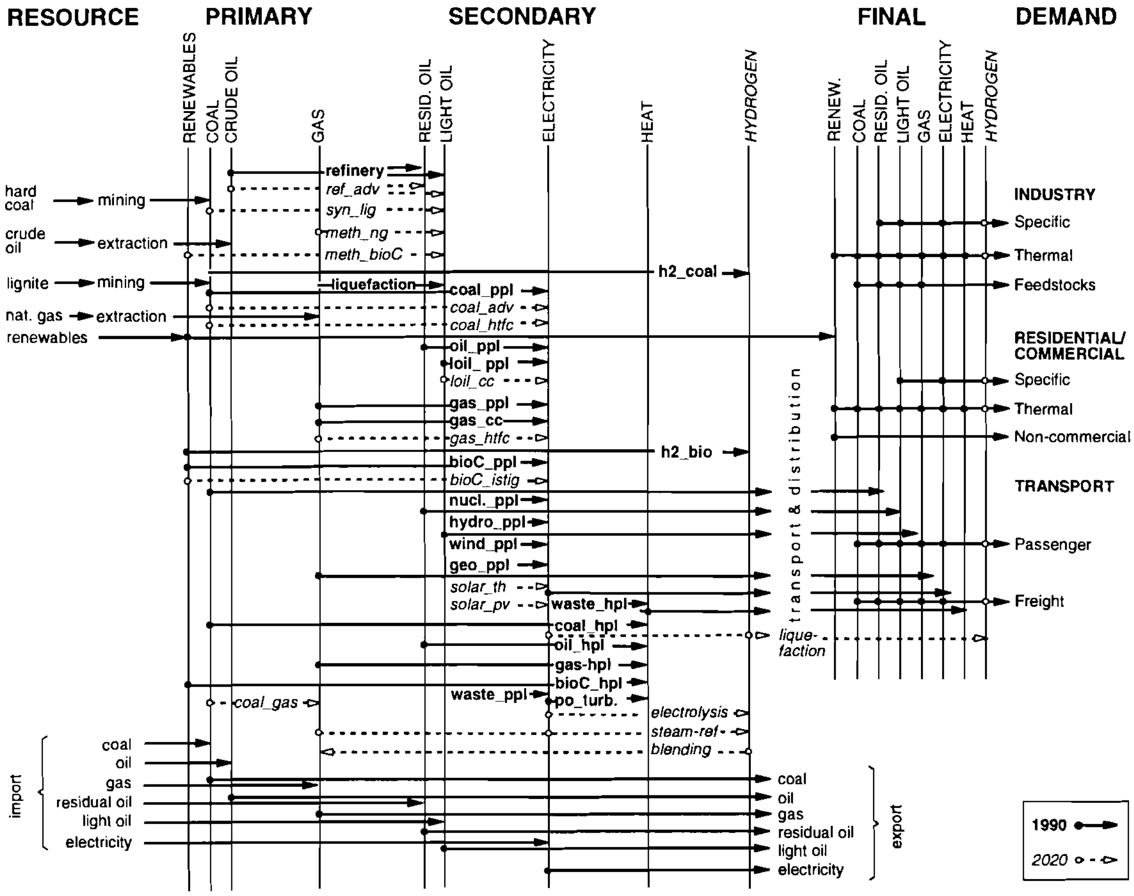


Figure 1: Schematic diagram of 11R including the Reference Energy System (RES). The RES refers to an oil-importing region. "E" and "NE" refer to electricity and non-electric fuels. "E^" and "NE^" are the production factors electricity and non-electric fuels. The relations between E and E^, and between NE and NE^ are discussed in Section 2.3. Dashed boxes indicate dummy technologies. These technologies are only specified by costs. No information is given about properties of interest for RES, such as conversion efficiency.



CENTRAL CONVERSION TECHNOLOGIES IN **1990**

coal_ppl	New (standard) coal power plant 90% flue gas desulfurization and 50% denoxing
oil_ppl	New standard oil power plant, Rankine cycle, low NOx and 90% flue gas desulfurization
loil_ppl	Existing light oil engine-plant
gas_ppl	Gas power plant, Rankine cycle
gas_cc	Combined cycle gas power plant with denoxing
bioC_ppl	New standard biomass power plant, Rankine cycle
hydro_lc	Low cost hydro power plant
hydro_hc	High cost hydro power plant
nuc_lc	Nuclear electricity generation, low (historic) cost
wind_ppl	Generic wind power plant, region specific
geo_ppl	Generic geothermal power plant (Asia)
waste_ppl	Waste power plant
coal_hpl	Coal heating plant
oil_hpl	Oil heating plant
gas_hpl	Gas heating plant
bioC_hpl	Biomass with net carbon release heating plant
waste_hpl	Waste heating plant
po_turbine	Passout turbine
refinery	Existing refineries (low lightoil yield)

ADDITIONAL CENTRAL CONVERSION TECHNOLOGIES BY *2020*

coal_adv	Advanced coal power plant, with 99% denoxing and flue gas desulfurization; can represent supercritical, PFB, etc.
coal_htfc	Coal based high temperature fuel cell (internal reforming)
loil_cc	Light oil combined cycle
gas_htfc	High temperature fuel cell powered with natural gas rejected heat available for co-generation
bioC_istig	Advanced biomass power plant: gasified biomass is burned in gas turbine plant with net carbon release
nuc_hc	Nuclear electricity generation, high cost
solar_th	Solar thermal power plant with storage
solar_pv	Solar photovoltaic power plant (no storage)
ref_adv	New deeply upgraded refineries (higher light product yield)
syn_liq	Coal liquefaction and lightoil synthesis
meth_ng	Methanol synthesis from natural gas
meth_bioC	Methanol synthesis from biomass with net carbon release
meth_bio0C	Methanol synthesis from biomass with no net carbon release
coal_gas	Hard coal gasification
h2_smr	Hydrogen production through steam-methane reforming
h2_elec	Hydrogen production through electrolysis
h2_liq	Large scale hydrogen liquefaction
h2_coal	Hydrogen production from coal via gasification
h2_bio	Hydrogen production from biomass via gasification

Figure 2.: The Reference Energy System (RES) for MESSAGE III: 1990 and 2020.

Macroeconomic relations fall outside the area of competence for the RES language. In *Figure 2*, the macroeconomy is a black box, which is also a sink for electricity and non-electric fuels supplied by the energy supply system. For our purpose, however, it is important that the way 11R is describing the energy supply system can be captured in a RES.

As expected, the RES for MESSAGE III has more technological detail than 11R. However, there are two important qualitative differences, which elicit the different modelling philosophies rather than the engineer's quest for details:

- *Technology links to the consumer.* RES identifies a chain of energy technologies that converts, transmits and distributes energy from resource to the final consumer. The steps in this chain can be identified as: resource->primary, primary->secondary, secondary->final, final->useful. Each step is connected with costs and energy losses. MESSAGE III describes all steps, albeit crudely for specific electric demands. 11R describes only the first step for non-electric fuels, but the two first steps for electricity.

- *Energy demands.* MESSAGE III identifies different useful demands which do not specifically require electricity. We will refer to these demands as "non-elc specific". Such differentiation is necessary to investigate changes in final to useful energy demands, e.g., fuel switching in the heating sector. 11R sees non-electric fuels as one single production factor.

2.2. *Common measuring points*

Our RES findings are summarized in *Figure 3*, which also provides the starting point for our linking. The diagram identifies the part of the RES which is common to both models. It also indicates which part of the RES is only described in MESSAGE III. In principle the common measuring points (CMP) could be chosen anywhere in the common area of the RES. The *purpose* of the soft-linking constrains the choice. E.g., for detailed sensitivity analysis we want the models to reproduce all the flows and capacities in the common area, and most nodes will have to be CMPs. To learn about the interactions between the two represented systems, we would probably prefer more autonomous models, and less CMPs.

Independent from the purpose of the linking, however, the *set* of CMPs will have some general properties that are important for a controlled soft-linking. To ensure model coherence within the whole common area, the set of CMPs should react to changes anywhere within this area. We will call such a set *inclusive.*[2)] To ensure swift convergence between the models, we would also like the CMPs to be independent from each other. This would simplify the procedures for model linking and quality control. A set with independent CMPs will be referred to as *exclusive.*[3)] Inclusive refers only to the common area, while exclusive apply to the complete RES.

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[2] An inclusive set of CMP has the following property: changing any energy flow or technology within the common area changes the energy flow at least at one of the CMPs in the set.

[3] To define an exclusive set, we introduce the concept of influence area. An energy flow or technology belongs to the influence area of a CMP, if a change in the flow or technology produces a change in the energy flow measured at the CMP. Two CMPs are exclusive, if there is no overlap between their influence areas. A set of CMP is exclusive if all pairs of CMPs in the set are exclusive.

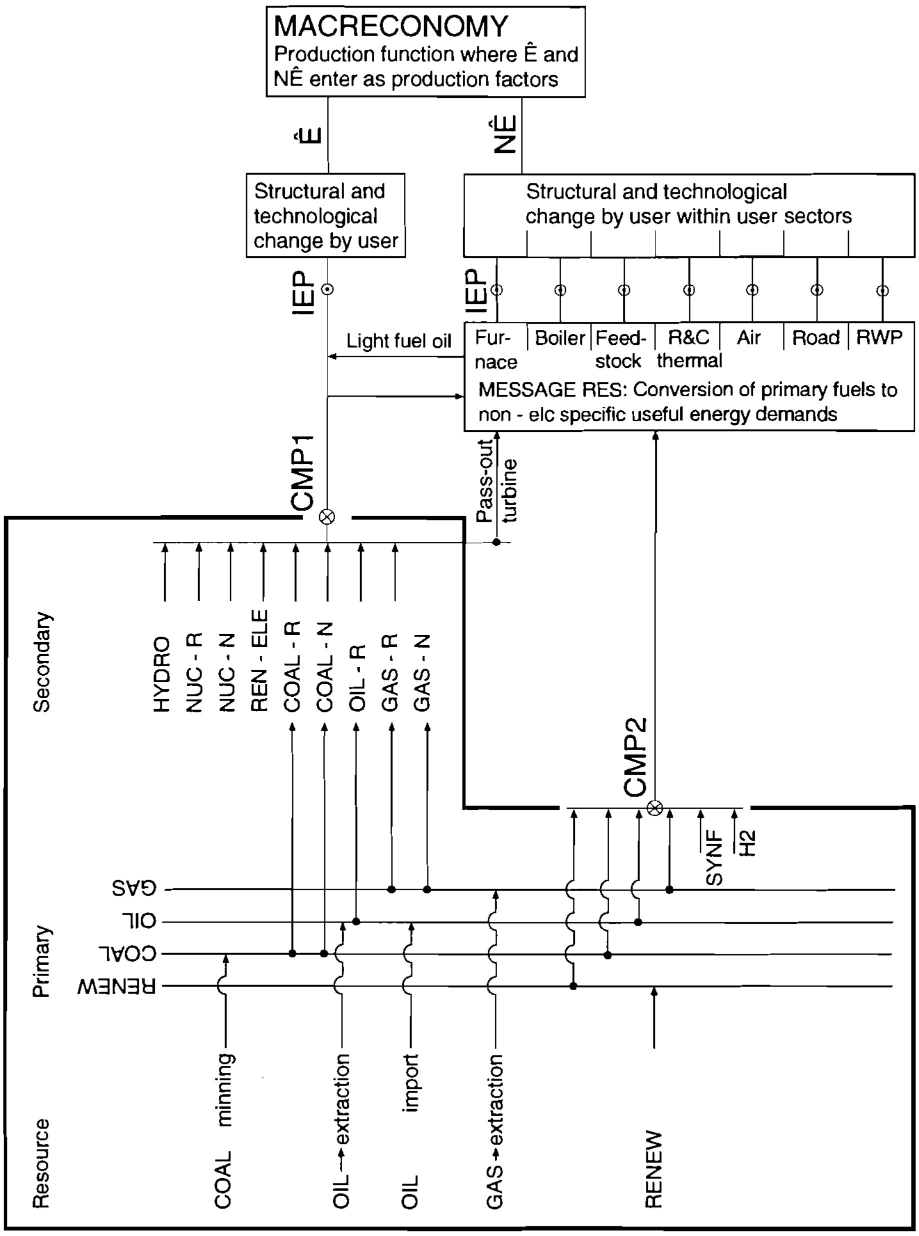

Figure 3: The common Reference Energy System (RES) and the coupling to the macroeconomy via MESSAGE III demands for commercial energy. The MESSAGE III RES can be mapped on the 11R RES from the resources until the common measuring points (CMP). Note the transfer of electricity to the non-elc specific sector in MESSAGE III. There is also a small use of light fuel oil in the MESSAGE III elc specific sector. Such cross-coupling between elc and non-elc specific demands makes is practically impossible to find an exclusive set of CMP, and contributes to soft-linking noise.

A non-inclusive set would leave part of the common area outside soft-linking. An inclusive set of CMPs is therefore a necessary condition for a controlled soft-linking. It would be desirable that the set of CMPs also is exclusive. Is this possible? The answer in most practical applications is no. The reason is that RES usually contains many vertical links connecting flows and technologies.

Figure 3 provides an example. The set consisting of the two points marked CMP is inclusive. However, it is not exclusive because the influence areas[3] of the CMP overlap: (i) for final energy through use of electricity for thermal demands and transportation and of light fuel oil for specific demands, (ii) for secondary energy through coupled production, and (iii) for primary energy through use of the same primary energy carriers for both production of electricity and non-electric fuels.

The fact that the set of CMPs cannot be exclusive has important consequences. The soft-linking procedures to iterate between the two models has to include corrections for the overlap between the influence areas. These corrections become fairly elaborate if there are large vertical flows in the RES outside the common area. The overlap between the influence areas results in soft-linking noise: also after several iterations there will be differences at the CMPs between the two models. The effect of a non-exclusive set of CMPs is further discussed in Section 5.

Looking at the common part of the RES as a black box (Ashby 1964), CMP sets consisting either of the inputs or the outputs from the common part is expected to be inclusive. Instead of using the sums of electric and non-electric fuels output as CMP, as was done in the previous example, one could measure the output from each generic electric technology and of each non-electric fuel. The set of such CMP is also inclusive. But it is still not exclusive, although the overlaps for primary and secondary energies have been reduced.

2.3. Translating between economic and RES languages

The previous analysis of the models is restricted by the necessity to use one common, formalised language, RES. This is sufficient to design the softlinking procedures. However, to be able to interpret the softlinking results it is necessary to understand how 11R describes the coupling between the physical flows of electricity and non-electric fuels and the production factors electricity and non-electric fuels. For this an economic language is necessary.

The model assumes an equilibrium between prices and demands for capital, labor, electricity and non-electric fuels at a base year (1990). The market share between electricity and non-electric fuels is determined by an external parameter, the value share, which in the model runs described in Section 5 has been kept constant over the whole studied period. The total use of electricity and non-electric fuels is determined by another external parameter, the elasticity of substitution between the capital-labor aggregate and the energy aggregate in the production function. For details see Manne and Richels, 1992.

Assume that the physical energy flows, E and NE in *Figure 3*, and the energy production factors, E^ and NE^, remains identical throughout the period. With fixed relative prices between the production factors, the demand for electricity and non-electric fuels would then grow at the same rate as GDP. But, according to *Figure 3*, there could still be changes between the points marked CMP and the box called "Macroeconomy", where electricity and non-electric fuels are interpreted as production factors. Between those points lies a major part of the MESSAGE RES and the possibility for structural and technological change within user sectors. Technology R&D and life style could be the agents of non-price induced changes. The relations between the physical flows and the production factors are now re-interpreted (Manne and Richels, 1992)

$$E(p) = E\hat{}(p) * \prod_{i=1}^{i=p} (1-AEEI(E,i)^{\Delta} = E\hat{}(p)*CUM(E,p)$$

$$NE(p) = NE\hat{}(p) * \prod_{i=1}^{i=p} (1-AEEI(NE,i)^{\Delta} = NE\hat{}(p)*CUM(NE,p)$$

where p is the model period and the length of the period, in our case 10 years. The new parameter, Autonomous Energy Efficiency Improvement (AEEI), is introduced to capture changes between the CMPs and the production function at constant energy prices measured at the CMPs.[4] CUM shows the accumulated effects in period p.

The analysis provides one important conclusion: it is possible to translate AEEI at least partially into RES-language. The MESSAGE model can be run with constant prices for electricity and for the fuels passing through the common measuring point for non-electric fuels in *Figure 3*. The changes in efficiency outside the common part of the RES is then the RES contribution to AEEI. The remaining part of AEEI is attributed to structural and technological changes within the sectors identified by MESSAGE III.

At changing prices, changes in the energy system are a result both of price, the production function and whatever driving forces behind the AEEI. Without a model for the user sectors, it does not seem possible to disentangle and translate the effects of economic parameters into RES language for this case.

3. Linking procedures

3.1. Soft-Linking and Hard-Linking

The discussion about a common language for system identification focused on the requirements for informal linking or "soft-linking". In soft-linking, the processing and transfer of the information passed between the models is directly controlled by the model users. The users evaluate the results from the models and decide if and how the inputs of each model should be modified to bring the two sets of results more in line with each other, i.e., how to make the models *converge*. It must be emphasized, that soft-linking involves two quite different modes of information processing: by formal models, and by linking procedures. The latter mode always includes an informally evolving, judgmental part. The term *Clearing House* is introduced to denote *all the activities and the information processing taking place outside the models with the purpose to link the models.*[5]

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4 This means that the price of E^ and NE^ will be reduced by 1/CUM(E,p) and 1/CUM(NE,p) respectively. At constant energy prices but with non-zero AEEI, there will be take back effects in the macroeconomy, leading to an energy demand that grows at a rate slightly larger than (GDP growth - AEEI).

5 Following the terminology of Checkland (1981), a model is a purposive, designed abstract system. But a Clearing House consists both of a designed abstract system, i.e., the softlinking procedures, and of a purposeful human activity system.

In order to decide on convergence there must be a set of common measuring points, CMP, as discussed in the previous section. To avoid *ad hoc* decisions, the Clearing House sets up strict procedures for output-input processing, using the CMP to control the linkage.

Before discussing the design of soft-linking procedures, a comparison with formal model linking is useful to further understand the advantages and disadvantages of softlinking.

In formal linking, or "hard-linking", all information processing and all transfer of information between the models is formalized and usually handled by computer programmes. In areas where the models overlap an algorithm may be used to negotiate results. Usually, however, one model is given strict control over the results, and the other model is set up to reproduce the same results. In a computer model, the subordinated parts are simply substituted for the corresponding parts of the controlling model.

The advantages of soft-linking can be summarized by *practicality, transparency and learning*. Likewise the advantages of hard-linking can be characterised by *productivity, uniqueness and control.*

Soft-linking seems the most practical starting point for linking models based on different approaches. Initial investments in computer programming are kept low, and the modellers can fairly quickly obtain results for evaluation and learning. But for reasons of productivity, hard-linking is the preferred end product. As the volume of model runs increases, and more model users become involved, more resources are needed to retain the quality of soft-linked than hard-linked models.

Hard-linking produces one unique result for each set of assumptions and data. Both assumptions and data can be well documented. The quality of the results can be controlled by reviewing these assumptions and data. Soft-linking will always produce some noise, because there will always be some differences between the models within the common region. Due to this soft-linking noise, uncertainty analysis becomes very difficult. In spite of stringent procedures, soft-linking always contains an element of human judgement. This complicates outside review.

Uniqueness and control come at a price, however. The advantage of softlinking is that at each stage of the exercise the user sees the perspective of both models; in our case the top-down macroeconomic model and the bottom-up systems engineering model. The top-down bottom-up controversy tells us that these perspectives may lead to different results. Hard-links decide beforehand which perspective should dominate when the models overlap. In soft-linking the differences are made explicit, as is the process of reconciling them. Soft-linking becomes a tool for learning about the system and the implications of the two perspectives.

Soft-linking and hard-linking can also be compared from the point of view of autonomy and coherence between the models. In hard-linking, model autonomy is subordinate to inter-model coherence. In soft-linking, the balance between autonomy and coherence is determined through the choice of CMP and soft-linking procedures.

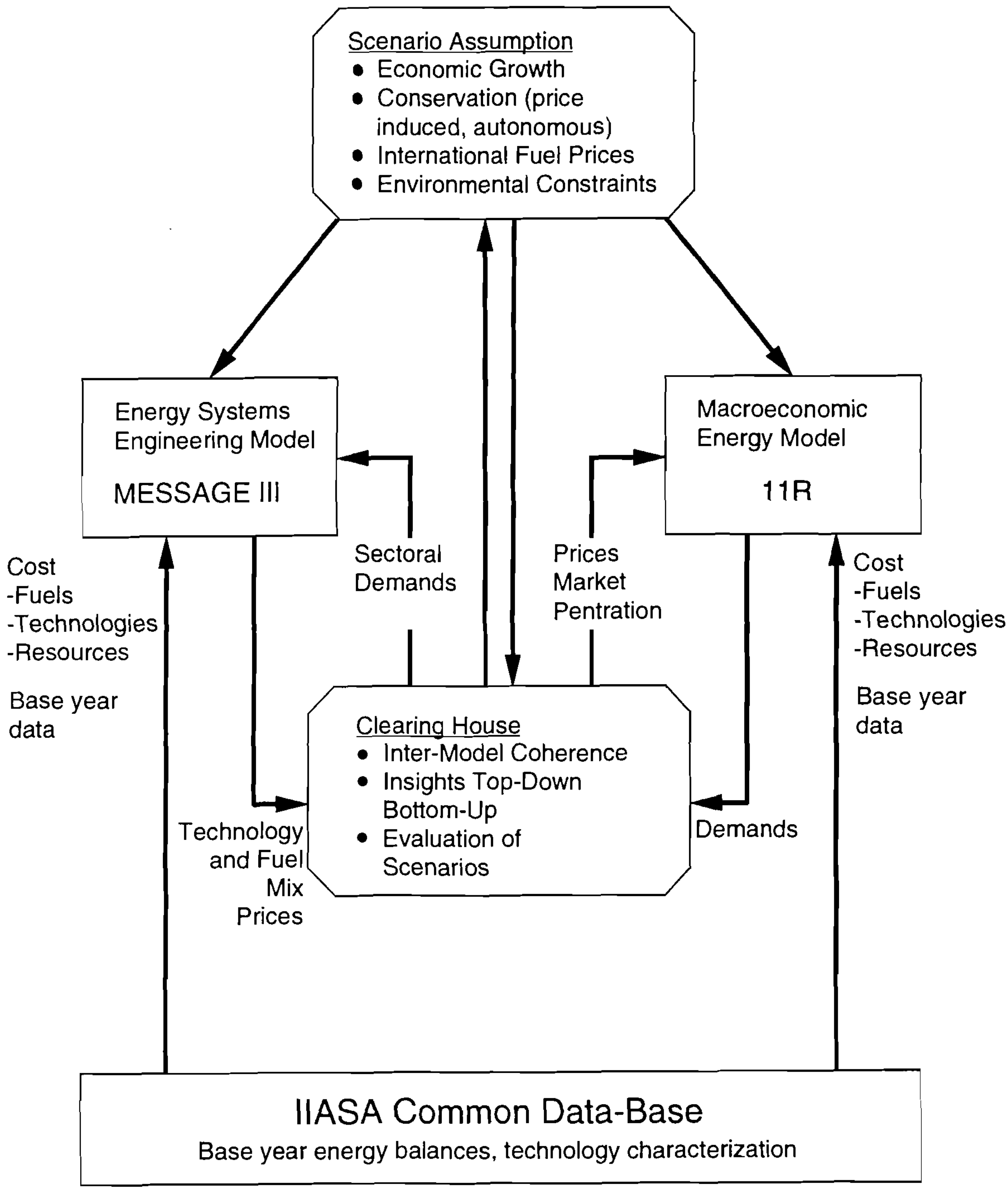

Figure 4: The Clearing House concept.

3.2. Clearing House and feedback controlled softlinking

Figure 4 shows the links between the models, scenario definition and the IIASA data base. The links are shown for one region. The steps involved in a computer run including softlinking are described in more detail in the Appendix. Here, we will focus on the links between the two models, including the Clearing House and the feedback control of the linking.

The Clearing House in *Figure 4* consists of the model users and the softlinking procedures. There is no direct connection between the two models, all information that is transferred between the models passes through the Clearing House. The Clearing House makes the judgmental and learning aspect of soft-linking explicit while emphasising the need for well-defined soft-linking procedures.

For the soft-linking of MESSAGE III and 11R, the Clearing House has three functions:

- *Procedures and Quality Control.* The Clearing House (CH) is responsible for the design and implementation of the softlinking procedures. This includes selecting the set of common measuring points. CH also reviews and documents procedures.

- *Learning about different perspectives.* The analysis based on the common language is used to distinguish between model discrepancies due to different formal treatment of data and discrepancies due to real differences in perspectives. Resolving the latter discrepancies gives insight into the top-down bottom-up controversy and helps improving the softlinking procedures. The example in Section 5 demonstrates this process for one region.

- *Scenarios.* The Clearing House support the scenario analysis through evaluation of individual model runs.

Figure 4 indicates the feedback control of the 11R-MESSAGE soft-linking. The process starts from an 11R run. The resulting demands for electricity and non-electric fuels are read off at the points marked CMP in *Figure 3.* This information is to be fed into MESSAGE in the form of useful energy demands at the information entry points marked IEP in *Figure 3.* The share of useful energy demands between the eight non-specific demands is part of the scenario assumptions, and the MESSAGE demands at IEP is calculated from the 11R demands using a spreadsheet model. For the first iteration with MESSAGE, the 11R demands are converted assuming that there is no change in efficiency in the RES between the CMPs and the IEPs. This means, that the known base-year efficiencies for transferring energy from CMP to IEP is used throughout the whole period. For the following iterations, the previous MESSAGE run is used to correct for efficiency changes in the conversion from CMPs to IEPs. Corrections also have to be made for the fact that the two CMPs are not exclusive, i.e., for the use of electricity in the non-specific sectors, for the coupled production of electricity and heat, and for the use of light fuel oil in the elc-specific sector.

The procedures used for the example in Section 5 allows only iterations between the Clearing House and MESSAGE III. The iterations are continued until MESSAGE III reproduces the original 11R values at the CMPs within a pre-set tolerance. It would have been quite possible to extend the set of CMPs, start iterations between the Clearing House and 11R, e.g., to make this model reproduce the fuel mix of MESSAGE. However, this would have complicated the soft-linking without shedding any new lights on the top-down bottom-up controversy.

It remains to discuss the choice of CMPs, IEPs and the meaning of the different corrections used in the conversion from 11R demands to MESSAGE III useful demands.

The selection of common measuring points and feed back points is done within the Clearing House. Although the inclusive-exclusive requirements provide some guidance for CMP, the choice will always have a strong judgmental element.

In our case, the purpose of the softlinking is twofold: (i) develop softlinking procedures for the IIASA Scenario project, and (ii) provide insights on the top-down bottom-up controversy. Both these goals call for initial softlinking procedures that retains a fair amount of autonomy for the individual models. As experience accumulates, the model coherence can be increased.

The selected CMPs form the smallest meaningful inclusive set[6]. They therefore give a large amount of autonomy to the models. It would be possible to directly constrain the MESSAGE III model at the CMPs to reproduce the 11R demands. However, this would give no information about the top-down bottom-up controversy, which we know is related to the energy flows after the two CMPs. The IEPs are therefore chosen as far downstream from the CMPs and as close to the "Macroeconomy" as possible.

The meaning of the correction for efficiency changes in the MESSAGE RES after the CMPs has already been elicited: it is the RES contribution to AEEI.

3.3 Other types of softlinking

The expression "controllable soft-linking" has so far been understood to mean "soft-linking that can be controlled by intercomparison of results from the models, i.e., it is possible to have an internal control of the link". This requirement for controllable softlinking seems necessary to link models that claim to describe the same object, e.g., the energy system. There are, however, other legitimate forms of soft-linking where the models do not claim to describe the same object.

Model chains are used to investigate causal links between different objects. One example is integrated modelling where the links between the energy-economic system and the Earth climate system is studied (Alcamo *et al.*, 1994, Hulme *et al.*, 1994). Another example are the modelling chains used to investigate possible releases of radioactivity from underground repositories for nuclear waste (Chapman et al., 1994). In these cases the model linking can be characterized as sequential soft-linking.

Many of the concepts developed above can be taken over to sequential soft-linking. A Clearing House is needed to develop linking procedures and ensure quality control. A common language is needed to identify points for measuring. In this case, however, these points need not be common measuring points. If they are, this indicates some overlap between the models, and the common measuring points also become the information entry points for the model receiving the information. If there is no overlap, a bridging interface must be designed by the Clearing House. Note that independent from any overlap, a common language is needed for quality control of the soft-linking.

4. Scenario and Scenario Control

Figure 4 indicates the control from the scenario meta-level on the models and the soft-linking. The scenario level must also provide closure for any remaining discrepancies between the two models after the soft-linking.

In the language of systems analysis, the scenario controls the boundaries of the models while the IIASA database provide system resources. The soft-linking is controlled by specifying the purpose (objective) of the linking. The purpose is interpreted in the Clearing House and used to find a balance between model autonomy and coherence. The balance is defined in practical terms through the choice

[6] Formally, the flows of electricity and non-electric fuels could be added and form an inclusive set with one member. It is difficult to ascribe any meaning to such a CMP from a thermodynamic point of view.

of common measuring points (CMP) and points for entry of information from the other model (IEP).

From the point of view of the scenario level, the task for the soft-linking is to check whether a suggested scenario is consistent and feasible. On this level, the rationale for probing into the top-down bottom-up issue is less to resolve a methodological problem, but to get a preview of model behaviour and an understanding of how to interpret the answers from the soft-linking process.

Closure at the scenario level has to be provided not only for softlinking within the 11 regions, but also among the regions for, e.g., traded energy carriers. To manage this task, model autonomy has to be reduced.

For the production runs, a master model has been designed using a language that is able to describe substantial parts of 11R and MESSAGE III. The master model interprets the scenario assumptions consistently for all the eleven regions. A Clearing House is set up on the scenario level to link the master model to the 11R and MESSAGE III models. Three sets of CMPs are defined: two for the linking of the master model and the 11R and MESSAGE models, respectively, and one for the linking of the 11R and MESSAGE. The CMP for the master and 11R models is the total primary energy demand, the CMPs for the master and MESSAGE III models it is the useful energy demands, and for the 11R and MESSAGE III the primary energy demands by source. The master model ensures coherence between regions and also reduces the softlinking noise between the 11R and MESSAGE III models at the individual regional levels. The price is that the regional models loose autonomy and some of their ability "to go out and find solutions for themselves". However, this is consistent with the view from the scenario level of softlinked energy-economy models as tools for checking the feasibility of scenarios.

5. Soft-linking at Work

5.1. An illustrative example

It remains to illustrate the practical application of the conceptual framework described above. Important questions concern the quality control. What does the balance between autonomy and coherence means in terms of model convergence and soft-linking noise? Given a set of CMP, how much and what type of feedback correction is necessary before one can say that the models are linked? We must also substantiate the claim that soft-linking energy and macroeconomic models can give insights into the bottom-up top-down controversy. For the illustration we choose the 11R-MESSAGE III soft-linking of the region China and Centrally Planned Asia.

The soft-linking procedures are described in Section 3.2. *Figure 5* shows the effect of soft-linking at the common measuring points, i.e., the total electricity production and the total demands for non-electric fuels.

The pre-set criteria for soft-linking prescribe that the MESSAGE III values at the CMP shall be within 3% of the 11R values. These criteria were met after several iterations. In Section 3.2, we anticipated two types of corrections to translate the 11R values at the CMP to useful energy demands at the MESSAGE III information entry points, IEP. It is now possible to see the magnitudes of these corrections.

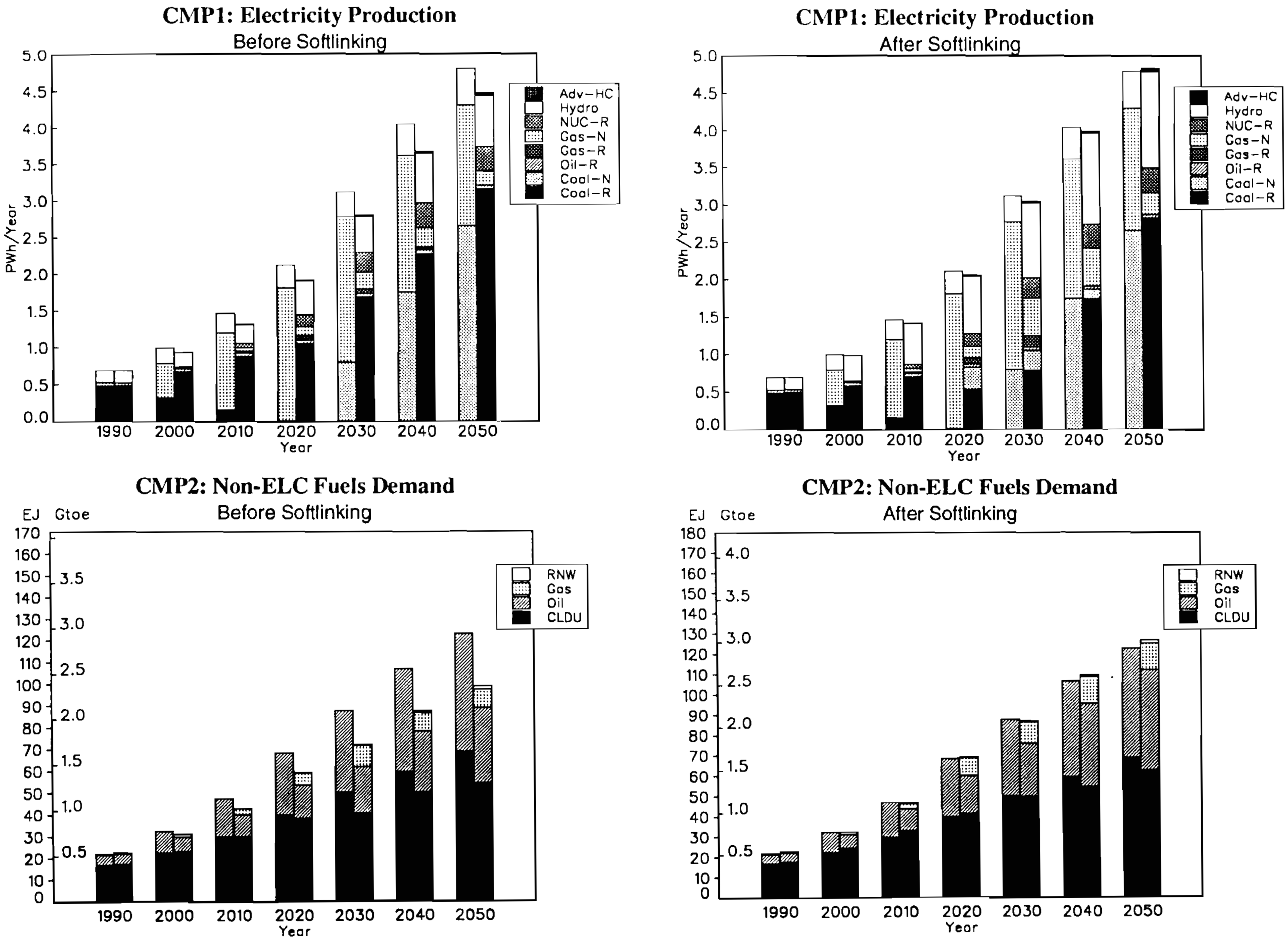

Figure 5: Comparison of 11R and MESSAGE III results at the two common measuring points (CMP). The two left diagrams show the results before entering the Clearing House, the two right diagrams show the convergence after iteratively applying the soft-linking procedures.

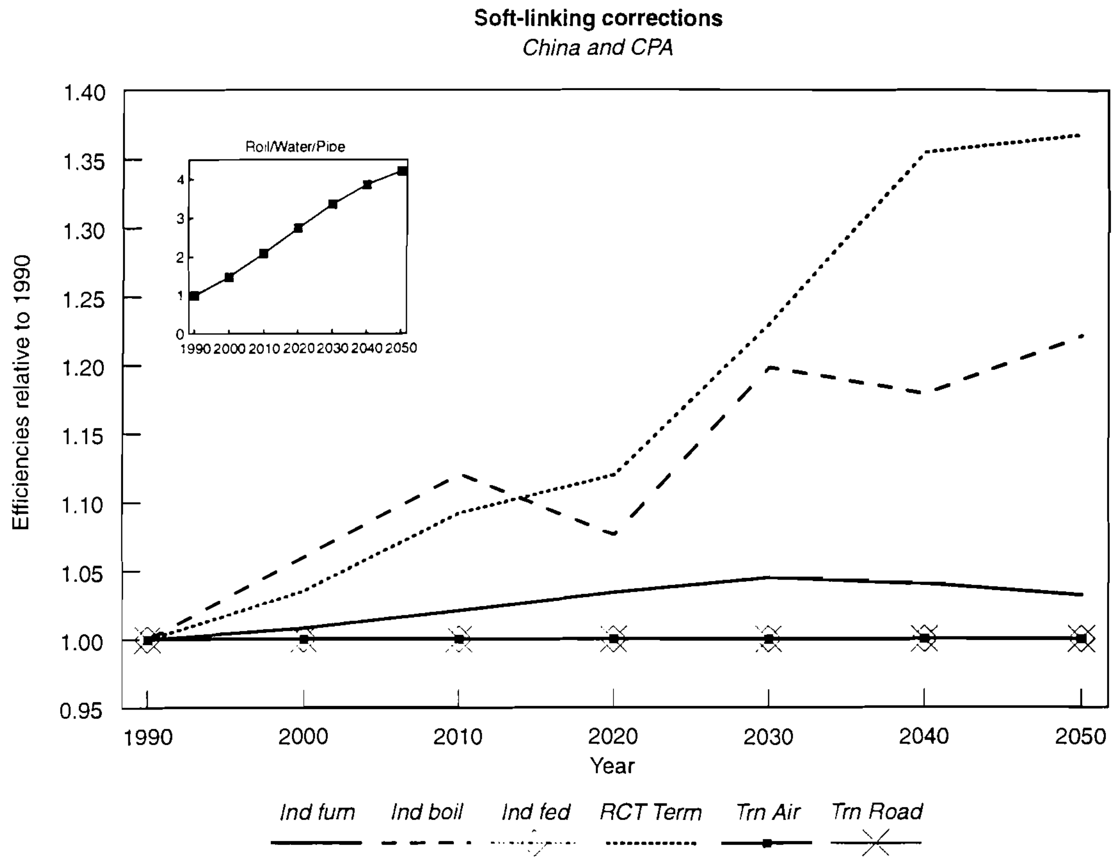

Figure 6: Soft-linking corrections for some of the non-elc specific demands. The diagram shows the changes in the total efficiency in the MESSAGE III RES between the common measuring point (CMP) and the information entry points (IEP) for non-elc specific demands.

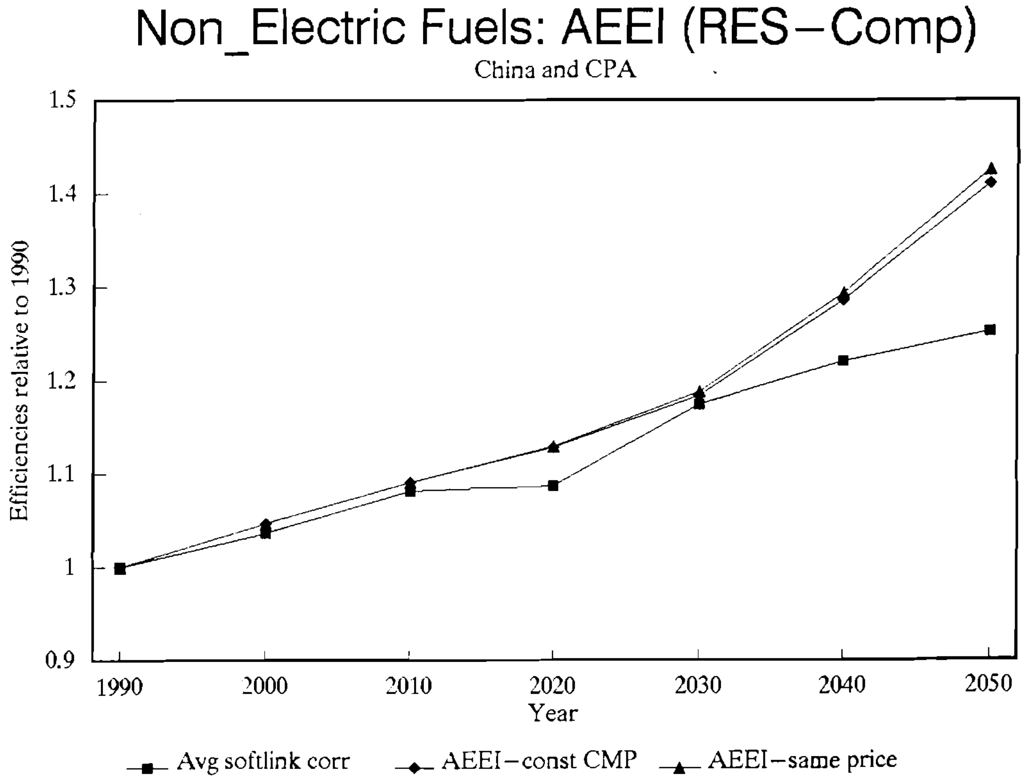

Figure 7: Energy weighted average changes in the total efficiency between CMP and IEPs for non-elc specific demands. The "Avg softlink corr" refers to the efficiency change for the linking in *Figure 5*. "AEEI-const CMP" and "AEEI-same price" are results from runs with two fossil fuels price schemes, which both give constant prices during 1990-2050 for electricity and non-electric fuels at the two CMPs.

The largest correction is due to *changes* in the compounded efficiency in the RES between the CMPs and the IEPs. *Figure 6* shows these changes for some of the useful energy demand categories used in the MESSAGE model. An analysis of the model results for non-electric fuels shows that all these changes are due to switching to more efficient fuel/technology combinations. The decision to switch is taken by the model, based on total cost. The changes in the electric sector are due to improvements in transmission and distribution and implicit already in the technology characterisation.

Figure 7 shows the total soft-linking correlation for non-electric fuels, i.e., the average effect of fuel switching in the RES between CMP and IEP. Applying this correction directly to the MESSAGE III results before softlinking would already bring the MESSAGE results within the 3% interval. However, for electricity the difference between 11R and MESSAGE would be up to 8%. The fact that the set of CMPs is not exclusive has a small but not negligible effect on the soft-linking. In order to soft-link the two models, second order corrections due to the overlap of the influence areas of the two CMPs have to be included in the soft-linking procedures. Most important is to account for the use of electricity for thermal purposes and some light oil in the "elc-specific" sector.

The choice of CMPs give the models large autonomy in choosing fuels and technology for electricity generation. A comparison shows that the market penetration of electric technologies is quite different in the two models. Differences in aggregation of fuel resources and technologies, and in the description of age structure are added and enhanced by the optimising algorithms. The differences in fuel and technology structures between the two linked models are examples of soft-linking noise. One way of avoiding this noise is to reduce model autonomy by choosing a larger set of CMPs. But this would complicate the interpretation of the efficiency correction, which already with the applied soft-linking procedures is clearly established above the noise level. The selected set of CMP is well suited to elicit the treatment of efficiency improvements in the two models.

5.2 Interpretation as Autonomous Energy Efficiency Improvement

The economic interpretation of the efficiency correction was discussed in Section 2.3. In the present case, energy prices increase substantially and change relative to each other. The average softlinking correction in *Figure 7* is then a result both of autonomous energy efficiency improvements, AEEI, and the changing share of non-electric fuels in the production function. However, running the model with fixed prices for electricity and non-electric fuels will make the soft-linking correction equal to the RES-component of AEEI.

Fixed price at CMP for non-electric fuels can be obtained in several ways in MESSAGE, because this model has three fossil fuels. *Figure 7* shows the result for two quite different price schemes. The difference is small, and we conclude that with plausible fossil fuel price schemes to keep the CMP price constant, the RES-component of AEEI implicit in the database used for this study can be fairly unambiguously defined.

Somewhat surprisingly, we find that the AEEI-curve lies *above* the curve showing the changes in efficiency in the original run. In the language of 11R, this implies that increasing the price of non-electric fuels leads to less efficiency improvements. Analysing the MESSAGE solution reveals the reason for the apparent contradictory result. 11R aggregates all non-electric fuels into one fuel which carries the price signal to the macroeconomy. However, most of the efficiency improvements are results of switches to more efficient fuel/technology combinations. The actual amount of switching will depend, not only on more efficient technologies becoming available, but also on the development of the *relative* prices between the non-electric fuels, which in our case primarily are the three fossil fuels: coal, oil and gas. The rising aggregate fuel price hides drastic changes in the relative prices. Disaggregation of the price for non-electric fuels into separate prices for the fossil fuels therefore dissolves the contradiction. The analysis illustrates the problems of unpacking a black box.

A more detailed study of the MESSAGE results shows that differences in switching to gas explains the differences between the two efficiency curves.

In the price schemes applied to extract AEEI from the MESSAGE database, fossil prices are artificially fixed at or close to the current values. There is little or no change in relative prices, indicating that the gas price is less or equal to the price for the other fossil fuels. As the more efficient gas technologies become available, they will therefore be chosen as the most cost-efficient alternatives. In the original MESSAGE runs, where price and availability of the fossil fuels are characterised by supply curves, the present cheap gas reserves are exhausted faster than the corresponding oil and gas reserves. Gas prices therefore rise quicker than oil and coal prices. In this case, the use of gas in 2050 is less than one third of the use at constant prices.

5.3. *Bottom-up and top-down treatment of energy-economic links*

From our experiment with MESSAGE, we draw three conclusions regarding the bottom-up and top-down treatment of energy-economic links:

a) Magnitude of AEEI.

The results imply a RES-component of AEEI of 0.6% per year. The RES-component includes the effects of structural changes between the MESSAGE demand categories. The results should be compared with the assumption of AEEI = 1.5-1.0 %/year used in the 11R runs. It leaves 0.9-0.4 %/year of the AEEI to be explained by structural changes within the MESSAGE demand categories. There may also be a residual technology component, because the RES does not describe technology changes within individual industrial branches. Only empirical studies can decide whether the numbers are plausible. However, the softlinking makes it possible to decompose the linking and pose more precise questions for these studies.

b) Methodology versus data.

Soft-linking demonstrates that data can only be understood by means of a methodology. The RES-component of AEEI is to a large degree the result of increasing market penetration of already existing gas technologies, which explains why efficiency decreases as the relative price of gas increases. This explanation needs a RES-based model. On the other hand, an economic model is needed to focus on the importance of relative changes in compounded efficiency to understand the linking between primary energy availability and gross production. Softlinking does not resolve, but dissolves the dichotomy of methodology and data: data designed for one methodology may not be accessible for another methodology without the mediation of the first methodology. E.g., engineering data on fuel switching and efficiency improvements must be translated or re-interpreted before entering into a macro-economic discourse. Without such re-interpretations, most discussions between the systems-engineering approach and the economic approach are meaningless. The results for the RES-component of AEEI is an example of a re-interpretation. The re-interpretations are major tasks for the soft-linking Clearing House.

c) The reductionist versus the black-box fallacy.

The RES language favours a reductionist view of demands. Demand categories are defined so that engineering data on energy conversion and distribution technologies can be entered as precisely as possible. In fact, as more demand categories are distinguished the more precise can the technology options be described. The reductionist fallacy lies in the belief, that the components of the compounded energy demands will remain the same in the foreseeable future. But within a time horizon of 50-100 years, there are historically many examples of emerging new demands. A production function oriented highly aggregated model like 11R allows for emerging demands. The soft-linking procedures, requiring convergence between the 11R and MESSAGE demands for electricity and non-electric fuels, provides some cure for the reductionist fallacy. But there is of course no explicit emerging demands in MESSAGE; any useful energy for emerging demands will be hidden in the 11R-corrected demands for the original categories.

The black box fallacy refers to situations with major changes in fuel and technology prices and availability as well as in system constraints, such as environmental requirements. This may activate or enhance alternative fuel-technology chains, giving the technical energy system properties not foreseen by a macro-economic model. In a RES-based systems-engineering model it will show up as a new or enhanced energy flow path. The situation on the oil market 1980-85 provides an example. Coal substituted heavy oil in the electric sector, and the displaced heavy oil fraction was cracked to light products such as gasoline and light oil. Treating the technical energy system as a black box, the system appears to produce gasoline from coal already at prices slightly over 20 USD/bbl. A systems-engineering analysis reveals, that the crude price is capped, not by emerging new technologies, but by conventional crackers and conventional coal condensing power plants working synergistically (Deam, 1985).

Our illustrative example refers to a dynamics-as-usual scenario which is a poor case for demonstrating the black box fallacy. But the results on efficiency changes provide some insights in the mechanics of the fallacy and how to avoid it. From the RES-based model, it is evident that low relative gas prices activate the gas paths with better efficiencies, while higher relative gas prices retains more of the coal and oil. If this is considered important, the macro-economic model can be re-designed to reflect the different efficiencies for the fossil fuels in the non-electric fuels paths. The point to be emphasized here, however, is *not* that all models are infinitely malleable, but that a systems-engineering model is necessary to call attention to the misrepresentation and to help decide if it has such consequences that the macro-economic model has to be improved. Soft-linking is one tool that addresses this task.

6. Conclusion

By identifying and starting from a common language, it has been possible to develop a rigorous methodology for feedback controlled soft-linking between a systems-engineering and a macro-economic model. Each model has a proven track record in global energy and environmental analysis. The soft-linking therefore provides a quality controlled tool with considerably enhanced capacity.

The soft-linking provides at least a partial translation into a systems-engineering language of an important parameter in the macroeconomic model. This gives a leverage for further studies of the links between energy and economy.

The question arise whether the different estimates for cost of mitigating global warming is due to differences in the methodology between alternate approaches or the data used in the analysis. The soft-linking indicates that this question is an egg-or-hen question: data is defined and collected by reference to a theory/methodology and is evaluated by the same theory/methodology. A meaningful discourse is only possible after specifying data, methodology *and* procedures for translating between the language of the two approaches. Soft-linking helps develop such procedures. Soft-linking also exposes the reductionist and black box fallacies, at the same time providing a tool to avoid them.

The concept of a Clearing House provided a focus for designing the soft-linking procedures, interpreting and documenting results, and controling the quality of the linking.

The Reference Energy System was used as a common language to soft-link the 11R with the MESSAGE III model. This choice of a common language restricts the applicability of the method described here to economic models where energy flows are described in physical terms. Other methods have to be developed to link, e.g., a general equilibrium and a systems-engineering model, but the requirement of a common language with part overlap between the models remains.

There is a growing need to analyse large or interconnected systems. In many cases there already exist well-documented and tested models for parts of the systems. Linking of such models seems to be more cost-effective than designing new models for the whole system or interconnection of systems. Soft-linking is in most cases an obvious starting point. However, our experiences also shows the shortcomings of informal linking. One is the soft-linking noise with the associated difficulties in uncertainty analysis. Another is the problem of maintaining the quality of the soft-linking as the model activities increase and the tool is transferred to other users than those developing the soft-linking. One remedy is to make the linking more formal to achieve in the end hard-linked models. Another is to use the soft-linked models as guides to develop a parametrised or otherwise simplified model for the larger system but with clearly set areas of application. In both cases, however, learning from a quality controlled soft-linking is the basis for the development.

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