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THE WELMM APPROACH TO ENERGY STRATEGIES AND OPTIONS

MICHEL GRENON
BRUNO LAPILLONNE

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International Institute for Applied Systems Analysis
2361 Laxenburg, Austria

PREFACE

Methods for comparing alternative energy strategies are insufficiently developed: optimization models, cost/benefit analysis, impact matrix preference functions. This paper presents the general framework of an impact matrix, WELMM (for Water, Energy, Land, Materials, and Manpower), that is being developed in the Energy Program, primarily to enlarge the scope of comparison of energy options. It specifies the approach that has finally been chosen to carry out the energy resource studies and therefore updates the various documents previously written on the WELMM approach [1, 2, 3, 4].

SUMMARY

The development of energy resources requires more and more natural or human resources: on the one hand because of the difficulty of "harvesting" primary energy resources, and on the other because of the complexity of the sequence of processes necessary to convert these primary resources into useful resources for an economy (final energy). In this context the WELMM approach has been designed to evaluate the resource requirements for the development of energy resources. WELMM focuses mainly on five limited resources: Water, Energy, Land, Materials, and Manpower. The WELMM evaluation is implemented at the level of the major facilities concerned in the harvesting and conversion of primary energy resources into final resources. All the WELMM data are stored in three different data bases (Resource Data Base, Component Data Base, and Facility Data Base). They are meant to be used to enlarge and complete the traditional economic comparison of energy processes, energy strategies or energy options.

THE SYSTEMS ASPECT OF NATURAL RESOURCES

The speed and pattern of the development of industrialized countries have been widely influenced by the abundance and low cost of the natural resources (water, energy, minerals, land, etc.) on which all of this development is based. The current life-styles and technological choices prevailing in such countries undoubtedly reflect this fact. One of the major issues that mankind must face in the long-term future is the progressive depletion of non-renewable resources--or at least the more easily accessible and reasonably cheap ones--and a growing scarcity of land and water resources. This issue is accentuated if one believes that most of the developing countries will choose the same pattern of development as the industrialized countries. This point has already been strongly emphasized by the Club of Rome and in various studies; people now generally recognize its importance and the necessity of both saving resources and seeking technological alternatives based upon resources that are non-depleting, or at least less limited.

The energy resource problem constitutes only one part of the overall resources issue. Efforts are now being made to recover and economize energy and to increase the energy resources and reserves by implementing new recovery techniques or developing new energy technologies. At IIASA, this problem has been analyzed more broadly, beyond the technological considerations, by identifying several options for an unlimited supply of energy. The comparison of options now under way seeks to identify the systems implications, or "the side effects that become predominant if these options are deployed in a truly large-scale fashion" [5]. This paper aims at presenting some concepts for tackling this problem by putting it into the broader context of all natural resources.

Without going into the debate on resource depletion, it nevertheless seems certain that we are entering a period of increasing costs for energy production, basic materials, commercial water and available land,* affecting all processing activities, from extracting natural or primary resources (see Figure 1)

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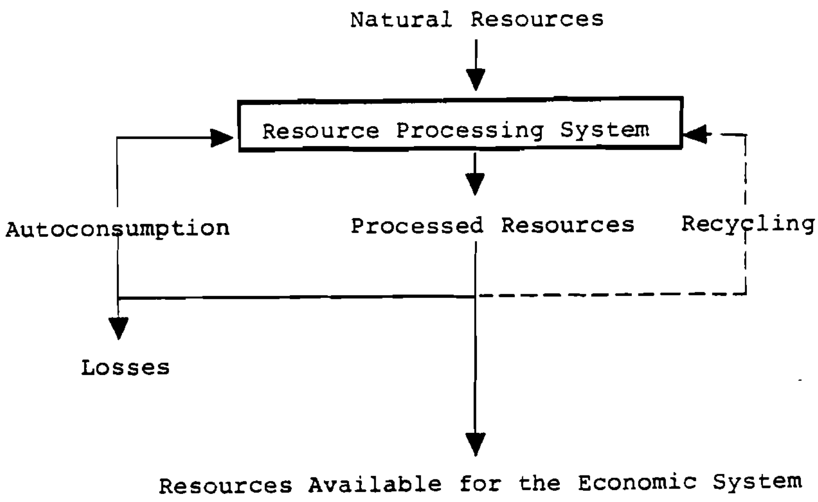
*We are not necessarily speaking here of market prices. The recent price increases for most raw materials due to political factors should not be confused with the cost increase to be expected due to other factors.



Resource	:	the production factors mobilized in a production process, or more generally in an economic activity, e.g. capital, manpower, energy, water,...
Natural (or Primary) Resources	:	the resources available in the natural environment: solar energy, coal, uranium ore, water, non-energy minerals (bauxite, iron ore), wood,.... For mineral resources, this includes the economic-geologic classification of resource base, resources and reserves
Processed (or Final) Resources	:	natural resources after transformation or upgrading (extraction or collection, processing, transportation, distribution, and possibly storage) to the condition in which they are consumed by the final user, e.g. final energy commodities, tap drinking water, basic materials such as steel, aluminium, glass, cement
Resource Processing System	:	a set of technological chains describing the linked series of activities necessary to make natural resources available to the final consumer (industries, households,...).

Figure 1. Natural resource cycle (basic definitions).

as they are found in the natural environment to final or processed resources as they are consumed in the economic system. Some of the most important factors responsible for this increase are:

- The necessity to exploit less easily obtainable resources (offshore oil, remote mineral ores in Africa or Oceania, oceanic nodules, etc.). So far we have been utilizing mainly the natural resources at hand; now, both extraction and transportation costs will tend to increase, though this may be partly counterbalanced by technological progress;

- The increase in processing requirements due, to the necessity of using resources of decreasing quality (upgrading lower-grade mineral ores, water treatment, possibly sea water desalination for some uses, and the like);

- Increased ecological constraints (reclamation of land disturbed by open mines, construction of wet, and later dry, cooling towers for large power plants, etc.).

All these cost increases will generally be expressed in an increase in the consumption of economic resources (processed resources, manpower, land, capital) and eventually also of natural resources.

Thus, if we consider the production and the conversion of natural into processed resources as the objective of a system which might be called the resource processing system (Figure 2), the primary resource efficiency or net primary resource balance of the system would be bound to decrease as it would consume greater amounts of natural resources for its own operation.

A major consequence of the resource scarcity is that the problems related to resource management cannot be analyzed by considering each resource separately: this would obscure the systems aspects of the problem. Rather, analysis must be done within a *global framework* integrating all the qualitative and quantitative interrelations of the natural resources. These interdependencies clearly lie in the technologies used to extract primary resources and to convert them into useful resources, each process defining a certain combination of resources and manpower.

All technological means of dealing with the problem of resource depletion for a specific natural resource--and especially for energy resources--should consider their impacts on other natural resources. This may reveal the possible constraints or bottlenecks that a technological strategy might create in the long-term, either at the global level (e.g. depletion of certain natural resources such as petroleum) or at a local level (e.g. water limitations in some countries of Central

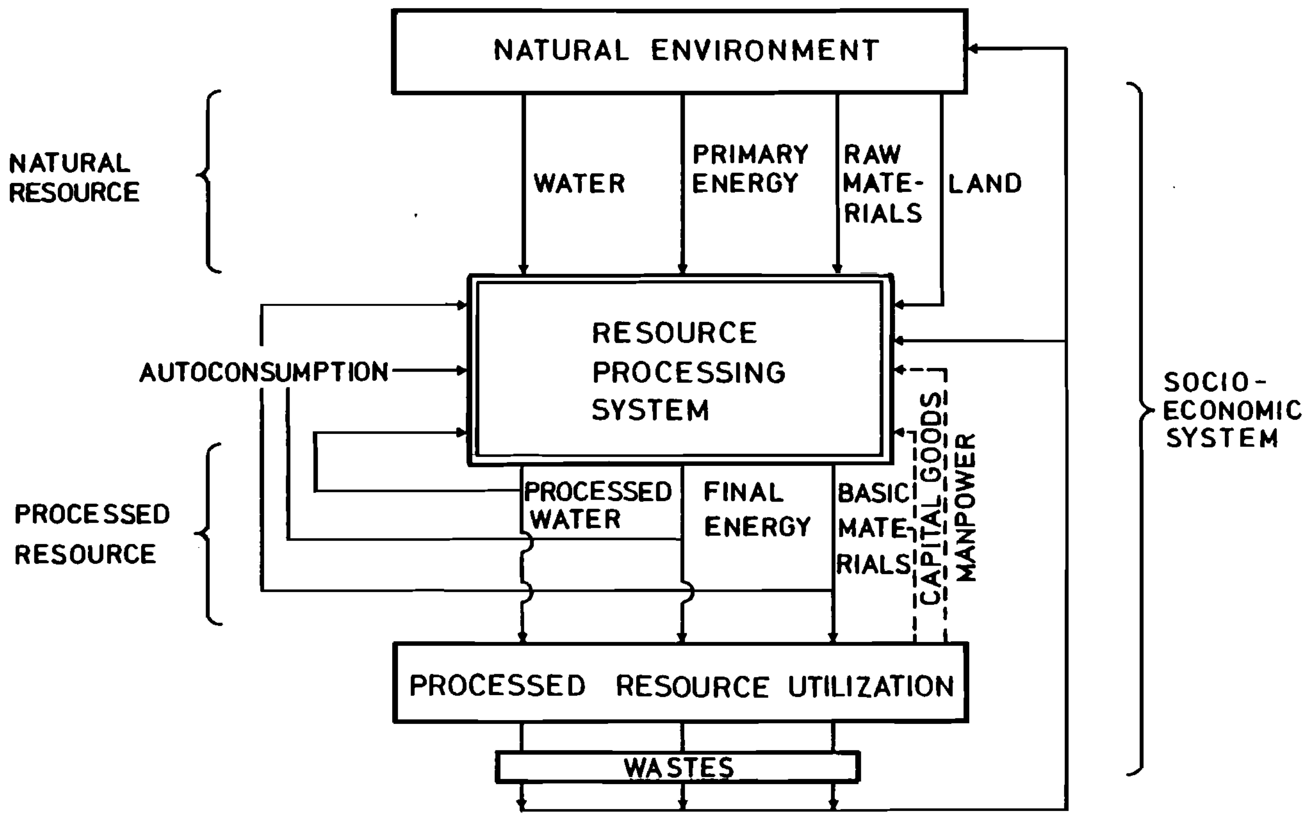


Figure 2. The resource processing system.

Africa and the Middle East; land scarcity in Japan, the Netherlands, or highly industrialized districts of a country such as the Ruhr area in the FRG).

In this context, the WELMM approach (Water, Energy, Land, Materials,* Manpower) has been designed as a means of analyzing the complex resource problem. The basic objective is *to assess the natural resource requirements of resource development strategies, especially energy strategies, within specific countries or regions or at the global level.* Because the natural-resource content of the capital mobilized in these strategies must be considered, WELMM can also help in assessing the impacts of resource development on economic systems; this is why manpower requirements are included. One can thus describe the objectives of WELMM as follows:

- Evaluation of water, energy, land, and materials requirements for development strategies;

- Analysis of the economic impacts of these strategies (capital and manpower requirements).

WELMM is only a partial approach to resource development assessment. It does not deal with the entire sphere that has often been mentioned for the deployment of energy strategies [6] but focuses on the impacts on the hydrosphere, the lithosphere, and to a lesser extent the ecosphere and the sociosphere. Moreover, WELMM does not deal with pollution impacts, which have recently been extensively addressed (see for instance [7]).

Table 1 is a (non-exhaustive) list of qualitative and quantitative relations between energy and other natural resources in the conversion of primary fuels to electricity. The WELMM approach aims at a better understanding of these interactions through their description in matrix format. It can be seen that practically all steps of the energy chains have interactions with the other natural resources selected.

To begin with water, the first impact that comes to mind is the water requirement for cooling power plants. In some countries these requirements have already reached or surpassed physical limits (Table 2). Water cooling is also used in various processes for upgrading and reprocessing fuels and for final waste management. Water is also used as a basic material in various phases of processing, which leads to added withdrawal and depletion. Also of growing importance is the interaction of mining

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*We prefer the more general expression "materials" to "minerals" so as to include e.g. wood and lumber, and to emphasize--when appropriate--the material balance or material handling problems.

Table 1. Systems aspects of an energy chain (mineral fuels, fossil or nuclear).

Resource / Activity	Harvesting Fuels	Upgrading Fuels	Transporting Fuels	Conversion to Electricity	Reprocessing and Management of Final Waste
Water	-Interaction with ground water resources -Land reclamation -Wastes and water pollution	-Water for cooling -Process water -Liquid wastes	-Waterways -Coal slurry pipelines	-Water for cooling (once-through or wet towers)	-Water for cooling -Process water -Liquid wastes -Possible interaction with run off and/or ground water
Energy	At all the steps, energy is used and must be deduced from the raw energy content of the fuel being harvested and used for obtaining the final primary energy efficiency of the whole chain.				
Land	-Surface mining -Deep mining (subsidence) -Infrastructure: roads related facilities -Waste storage	-Facilities	-Roads -Rights of way: railways H.V. lines -Underground pipelines	-Facilities (siting problem) -Wood, lumber for construction	-Facilities (siting problem) -Waste storage
Materials	-In equipment and facilities, materials investments at all steps (problems of future recycling)				
	-Consumed materials -Materials handling and control -Waste	-Materials control and balance -Chemicals -Waste	-Pipes, cars, tankers, etc. -Materials handling	-Consumed materials -Problem of recycling	-Consumed materials -Chemicals -Materials accounting (possible safeguard) -Waste

Table 2. Example of interaction between energy and water resourc maximum electrical capacity that can be cooled with onc through cooling systems. (Based on 50 m^3/s per GW(e), but to limit the temperature increment of the rivers, twice the traditional amount of cooling water should be available, i.e. 100 m^3/s; 10°C increase of water temper ature in the cooling system and 33% efficiency assumed.

Source: [8]

Country	Average Runoff (m^3/sec)	Reference Ceiling [GW(e)]	Reference Ceiling Reached*
UK	2,100	21	1950's
FRG	4,000	40	1960's
USA	53,000	530	~1980

*These dates represent the approximate time at which a shif to cooling tower and sea cooling is required.

activities and water resources. In some areas, the mine is firs of all a true mine...of water. Garsdorf (FRG) in the Rhine lignite basin, where the aquifer has gone to a depth of 300 meters, illustrates this very well.* In other areas (e.g. the Northern Plains States of the USA), the reclamation of strip-mined areas competes with on-site coal conversion for water resources; and in the case of the Wyoming-Arkansas coal slurry project, it is proposed to tap underground aquifer at 1000 m deep.

*Lignite extraction in Garsdorf necessitates the pumping of a huge quantity of water: approximately $350 \cdot 10^6$ m^3 annually for the production of only $15 \cdot 10^6$ tons lignite. [4]

Compared to agriculture, energy is a modest land user. But with the growth in energy consumption, the siting of large energy conversion facilities is becoming a major issue, as are aesthetic questions and the problem of right of way for aerial corridors for high voltage power lines. As for water resources, mining activities--especially surface mining, of growing importance for energy minerals and representing 95% of the total non-fuel mineral production--have a severe impact on the land (cf. Figure 3). Conflicts in land use are becoming more and more frequent, and call for a deeper understanding. The land use issue is illustrated in Table 3 by comparing land requirements for three types of power plants. Water and land resources have been frequently examined in recent years, at least on a local or regional basis. The materials problem seems to be much less well understood, particularly in its systems aspects: material supplies, material recycling, waste disposal, material balances, material handling, basic equipment (steel pipes for oil drilling in the US or for oil or gas transportation in the USSR, coal cars for Western coal in the US, etc.). Our preliminary studies have shown that detailed assessments of the direct and indirect requirements for materials and their handling could play a major role in the comparison of various energy options, and especially for the solar option (see Table 4).

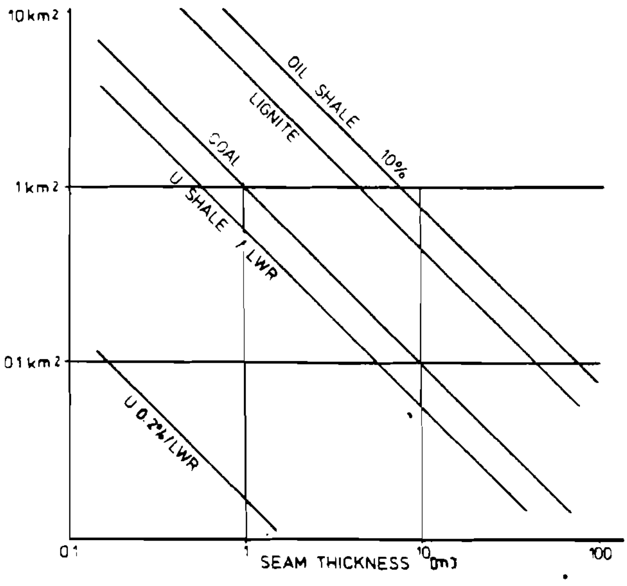


Figure 3. Land disturbed for producing 10^6 t.c.e.

Table 3. Land requirements for a 1000 MW(e) power plant.

Source: [4]

Fuel	Attribute	Specification	Area (km^2)	Type of land use
Coal	Strip Mine	2 m Seam 10 m Seam	25 5	Temporary
Solar	Tower Concept	4 $kWh/m^2/day$ 20% efficiency	30	Temporary
Nuclear	Site		0.08-0.5	Permanent
	LWR-U Shale	2 m Seam 10 m Seam	37 7.5	Temporary

Table 4. Materials requirements for a 1000 MW(e) power plant.

Source: [4]

Fuel	Weight of Station (10^6 t)	Total Flow (10^6 t)	Comments
Coal	0.3 - 0.35	50	Coal (25 years)
Nuclear	0.5 - 0.6 LWR FBR	2.5 - 75 0.04 - 1.2	U 0.2% - U Shale (25 years)
Solar (Tower)	0.35 (Conversion) 0.3-3 (Heliostat)	1 - 30	Mineral Ores (~5-7 years)

To build and operate all these facilities for harvesting the primary energy, upgrading and transporting it, converting it into final (or secondary) form and processing the waste, a lot of energy is needed, which decreases the primary energy efficiency.*

*Many publications on "energy analysis" deal with such estimates of energy requirements (see e.g. [4]).

The additional facilities to carry and process the water, prepare and restore the land, and process the materials must also be accounted for, although their relative contributions are obviously of decreasing importance (what is sometimes called the "principle of converging series").

THE PRINCIPLE OF THE WELMM APPROACH

The WELMM approach consists first in the *description and quantification*, where possible, of the interrelations among natural resources induced by energy activities. This analysis entails the collection of qualitative information on the primary energy resource potential, in order to study the impact of energy consumption on the resource stock; and the identification of WELMM requirements for processing these primary into final or processed resources. In the latter case, the data are collected at the level of each technological process.

All the information is gathered into three data bases:

- The Resource Data Base (RDB), on primary resource availability;
- The Component Data Base (CDB), on the WELMM requirements for the production of basic materials and typical capital goods;
- The Facility Data Base (FDB), on the direct WELMM requirements for construction and operation of energy facilities. It includes the requirements for production of both capital goods constituting the facility and basic materials used for operating the facility and manufacturing the capital goods.

Second, these data bases are used in *resource evaluation for energy alternatives*. Two main applications are considered: evaluation of resource requirements for large-scale development of local energy resources, and improvement of comparisons of energy technologies, regional or national strategies, or global energy options.

The WELMM Data Bases

Before being computerized, the data bases must be compiled in files. Standard file formats corresponding to the three data bases have been developed and are now being tested using data on selected resources, components or facilities.

A large part of the information required is generally available--though it may have to be processed to fit the WELMM format--or is being obtained for the numerous analytic programs for energy strategies, national or international materials policy (cf. discussions on New Economic Order), water and land management, etc. A basic problem is to make all these pieces of information coherent with each other and, if possible, more reliable by means of thorough critical analysis. If this first step proves successful, the main data will be computerized. Through discussions with other organizations (e.g. The World Energy Conference, the US Geological Survey, The Institut Français du Pétrole), we are meanwhile reviewing existing data bases, whether computerized or not.

The Resource Data Base (RDB)

The RDB is "opened" by the energy and the mineral resources. We are exploring the possibility of opening it through the other natural resources; manpower is not systematically included for the time being. It is planned to store only data related to WELMM assessment for energy strategies, as shown in Figure 4. If possible, connections will be established with other data base systems of global scale (for instance, the "Manifile" of the University of Manitoba for world nonferrous metallic deposits) or regional scale (the US National Coal Data Base), through a data base management system such as DILOS of the Computing Center of the USSR Academy of Sciences.

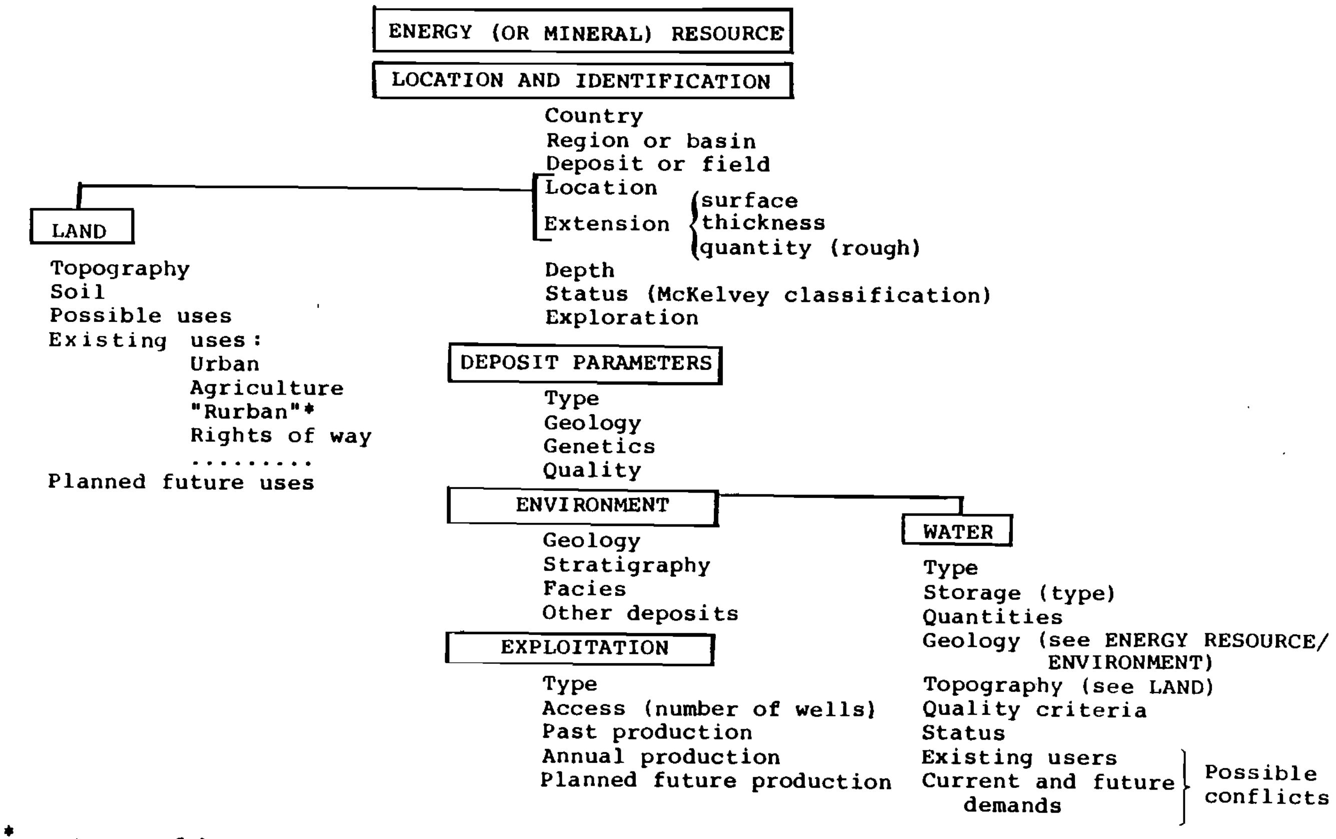
Apart from some special applications (for instance, a case study for regional development, not initially based on energy resources), the data will be collected by country. The countries to be analyzed will be selected through energy resources criteria analogous to those used for our coal studies [9], in which we chose about 30 countries having declared more than 1 billion metric tons equivalent of coal resources.

The data of Figure 4, while tentative, show the emphasis on WELMM impacts if energy resources are exploited. Similar data for land and water will be registered for the other energy facilities along the energy chains.

The Components Data Base (CDB)

This is the first step of "natural resources accounting", inspired by the well-documented "energy accounting" or energy analysis. As far as applicable, we are calculating or measuring through direct analysis the natural resource content of basic materials (e.g. water, energy, mineral content of steel or aluminum) or basic components (pipes, pumps, heat exchangers, turbines).

For materials accounting, the analysis goes as far as the raw material or the mining process. For stainless steel, for instance, we are assessing the total impact of mining iron, nickel, chromium ores and coal, and of possible overburden to be handled or disposed of, depending on the type of mining.



*new types of human settlements in rural areas

Figure 4. Basic concept of the WELMM Resource Data Base (RDB).

For some materials, energy content, water content, and mineral content are well documented, and our main task is to collect and review the data, and often to render them coherent. For land, a special analysis will have to be made, based on the process used for energy strategies. Chains of processes (to be described) will be identified--say, mining (iron, nickel, chromium ores and coal, for instance, for stainless steel)--and "land accounted" to permit assessment of the land content of one unit of composite or basic material. (See Appendix 2 for the content of this data base).

A component is defined as any major piece of equipment used in the subsystems of a given facility; for a power plant, for example, we consider building, boiler, turbine, generator, cooling towers, and so forth. Different processes or facilities, such as the light water reactor (LWR) or a coal fired power plant, often have some identical components (turbogenerator, cooling tower); and for different chains some common components can also be found (pipe network for oil and hot water transportation).

The type of equipment to be considered will depend mainly on the available data: clearly each energy facility cannot be disaggregated into a great number of individual pieces of equipment. Where such detailed information exists we will use it*; but where it does not, we will consider major equipment categories (cf. Appendix 1). For each category a rough estimate of the WELMM requirements per unit of output will be made, using available input/output models. For example, for electrical equipment the WELMM analysis will consist in evaluation of the average energy, manpower and materials requirements to produce one unit of output in the electrical industry. In general, we will neglect the land and water requirements, since the use of these two resources is very limited (compared to mining operations, or even to energy infrastructures).

For a given facility, the correspondence between components for which direct accounting exists and those for which it does not will be established by decomposing the capital cost. (For the basic files for this data base, see Appendix 3.)

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*An extensive components study for LWR reactors has been carried out by Electricité de France and made available to us. More and more direct accounting of resources requirements is being done (cf. Battelle [10], Bechtel [11]).

The Facility Data Base (FDB)*

An energy process and the associated facility are analyzed in terms of WELMM to bring out the whole set of resources required for operating and constructing the facility: the *direct resources*. These encompass the resources consumed where and when the facility is built and is in operation (on-site resources), those consumed in the manufacture of the capital goods of the facility, and those consumed for the production of all the materials involved at any of these steps.

Indirect resources refers to those required for the investments induced in related industries (basic materials or equipment industries) by the deployment of energy strategies.

The basic file for WELMM analysis of an energy process and/or facility is given in Appendix 4. A few case studies on typical facilities are being made to judge the value and practicability of such a file. One difficulty is due to the fact that the available information comes from various sources. Most of them are of US origin, but we are cross-checking these data with non-US organizations** in Europe and elsewhere.

Because of scale effects, there is a decided trend towards "standard classes" of facilities, such as the 250,000 t.d.w. (tons dead weight) oil tankers, the 1000 MW(e) nuclear power reactor, coal unit trains, and the 10 million ton refinery. In their Energy Supply Planning Model [11], Bechtel identifies 91 such energy-related facilities, 66 energy supply facilities, and 25 energy transportation facilities; some of them, for instance at the production level (oil wells), are already relatively aggregated.

There follow a few comments on the various resource requirements associated with a WELMM analysis (Figure 5), some of which apply particularly to operation (process analysis).

Primary input: As we are here looking at the energy process, the main inputs of all the facilities are energy commodities, either energy resources or secondary energy products.

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*Work on the FDB is done in close cooperation with Y. Kononov and takes into account investigations such as the Irkustk model [12] and the Bechtel study [11].

**We are cooperating closely with French organizations (Délégation Générale à l'Energie, Electricité de France, Commissariat à l'Energie Atomique, Institut Français du Pétrole, Bureau de Recherches Geologiques et Minières, Charbonnages de France, etc.).

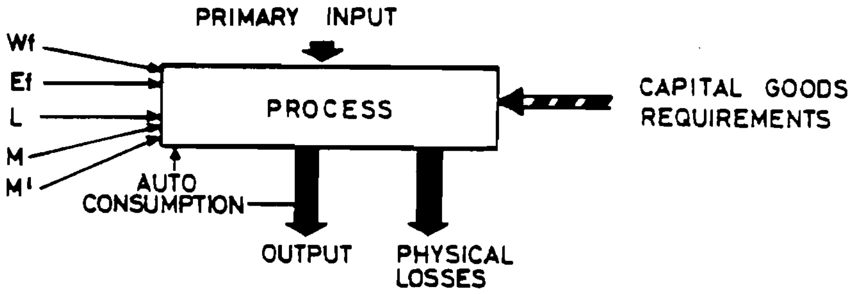

Figure 5. Process analysis.

Water requirement Wf (f denotes a final energy commodity and not a primary energy resource): Most industrial processes require water. Identifying the source of the water and possibly transporting it can be a major problem, as in the planned large-scale uses of US Western coal or industrial developments in arid regions, or even sometimes in hyperindustrialized areas (cooling for nuclear). Thus, each process is characterized first by its *water intake.*

Sometimes a fraction of the water input is consumed in the process, i.e. not returned to the source (with the cooling towe for example); water input data are therefore supplemented by *water consumption data.*

Dealing with water quantities may, in some cases, be insuf cient: These requirements may correspond to a certain *water quality* which should then be specified. Most often, the water use modifies or deteriorates its quality and causes pollution, and the water must be treated before it is disposed of. This aspect will not explicitly be taken into consideration in the WELMM analysis; it is part of the ecological impact which is being comprehensively studied [7,17]. In many cases, temperatu differences between inlet and outlet can also be of value, and will be included in the WELMM accounting as far as possible.

Energy requirements Ef (f again denoting a final energy commodity) and energy efficiency: As shown in Figure 6, Ef represents ancillary energy consumption, and does not include autoconsumption, which is taken into account in primary efficiency. Two types of ancillary energy are considered: electricity (specific uses), and fuels (coal, diesel, other oil products,...).

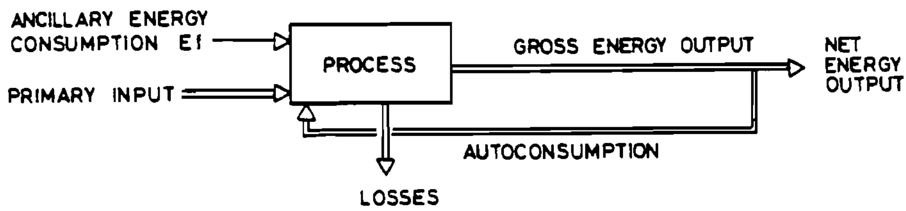

Figure 6. Energy requirements and energy efficiency.

Primary efficiency is the ratio of net energy output to energy content of the primary input*. It captures the fraction of the energy content of the commodity entering the process that is recovered after this process. The net energy output represents the difference between gross energy output and autoconsumption (e.g. electricity produced by a power plant and used for pumping cooling water, or heavy fuel oil consumed in an oil refinery). The net efficiency is the ratio of total energy consumed (primary, ancillary and losses) to net energy output.

Land requirements: We distinguish between *exclusive* and *non-exclusive* uses of land; for instance, aerial electrical corridors do not exclude farming. Concurrent use--for example, by hydroelectric reservoirs for power production, agriculture, and recreational activities--is considered non-exclusive.

A time dimension will be added to these two categories: *temporary use* refers to land use during construction and for the lifetime of the facility, and long-term use or *permanent use* to use for radioactive waste storage or as nuclear reactor sites if the reactors are not decommissioned. Moreover, it would be useful to specify the type of land that is to be used: urban area, agricultural, recreational, desert, etc.

Materials requirements M: Materials accounting includes consumption of the main raw materials, renewable equipment (with lifetimes of less than a year or so) and main equipment. Analysis concerns composite materials (steel or concrete) and basic materials (iron, nickel, cement, aggregates). With the CDB it is possible to go from the basic materials to the total mining requirements and material handling.

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*The primary energy efficiency concept is also useful in studying not an energy chain but a materials chain.

We also include quality criteria, as they are becoming more important but differ widely for the various energy alternatives (nuclear fission and fusion are certainly more demanding in qual itative terms than solar energy). The recycling potential of some materials will also grow in importance: irradiated materia are penalized in this respect.

Waste production in WELMM is not handled systematically, as it is in other studies [7,13,17], but more in terms of material handling. These considerations, as well as materials accounting (important in the nuclear case, or for the thermal production of hydrogen, etc.), will be handled qualitatively and/or quantitatively, depending on the various cases.

Manpower requirements M': Manpower requirements (expressed in men and man-hours) comprise "critical workers" (manual worker engineers, miners) and others. "Critical" manpower is introduce to bring out possible bottlenecks in the large-scale development of strategies due to manpower limitations (nuclear development, for instance, is now facing a problem with respect to the potential of qualified welders).

WELMM Applications

As has been mentioned, two major types of application are planned for the WELMM approach. The first deals with the resour assessment of regional projects for developing natural energy resources, what we might call " strategy assessment" (by analogy with technology assessment studies). The second considers the WELMM analysis as one component of comparative studies for energ alternatives (technologies, strategies*, options).

Natural and Human Resource Requirements for Development of Local Energy Resources

Because of the escalating costs of exploration and exploita tion of energy resources (and also, of course, because of the increasing levels of energy consumption), there is a trend to concentrate on the most profitable deposits--generally the largest--and to exploit them intensively. In the Middle East, for instance, oil deposits were exploited on a basis of 2-30% per annum (for 30-50 years); in the North Sea (and also, progressively, in the Gulf of Mexico) there is a trend towards 8-12% per annum (for about 10-12 years).

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*As opposed to *option*, which has a static meaning, a *strategy* implies a time dimension for its implementation.

Remote (Alaska) and offshore (North Sea) operations lead to ever larger WELMM requirements. A North Sea production platform can weigh one million tons (concrete and steel) compared to the few tons associated with a normal onshore field; and energy expenses have grown in a similar way.

The trend toward high concentration and intense exploitation could still grow, especially if giant additional petroleum resources are exploited, such as the Orinoco heavy crudes, the Colorado oil shale, the Athabasca tar sands, the Gulf of Mexico geopressure zones. The idea of a nuclear hydrogen "Canton Island" [14] or of the Greenland hydropower plant [15] also tends in this direction.

Such exploitation will be tremendously resource consuming in terms of materials requirements and handling problems for oil shale and tar sands*, land disturbance, energy balance (as much as one third of the recovered oil can be used for the enhanced recovery of heavy crudes), water management (one well in a geopressure zone can produce as much as 50,000 bbl of water per day).

As a first step toward dealing with this problem, and as an example of the method, we will make a detailed engineering WELMM assessment of one or possibly two of these huge petroleum resources. Our attention is especially focused on Venezuelan Orinoco heavy crudes and Gulf of Mexico geopressure zones.

Finally, it is worth mentioning that such an approach is not limited to energy resources and could easily be extended to or used for other resources. In addition to assessing the WELMM requirements of giant mineral deposits, which we also intend to do, it could be used for large water storage projects, food and agricultural developments, and the like.

Comparison of Energy Alternatives

Before describing the various WELMM applications, it is worthwhile specifying the contribution of the WELMM approach to processes of comparison, whether by traditional economic methods or by multicriterion analysis. In the traditional economic approach, WELMM must be viewed as a way of completing and improving comparisons. It brings out new constraints related to resource utilization that are difficult to account for in the calculations. This is especially true for long-term studies, for which economic comparison (cost-benefit analysis or optimization models) very rarely leads to a unique solution because of the uncertainties in the costs of some inputs (several variants in oil price must be considered, for instance). In this context, WELMM might help, through qualitative considerations, to identify

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*The same would apply to Chattanooga uranium shale.

the most suitable alternative in terms of the long-term resource availabilities and industrial constraints of a country or region. It can also show more precisely the degree of political and technological dependence for each alternative (e.g., the necessity of importing certain types of materials or minerals, manpower dependence).

WELMM can improve comparisons in allowing us to take into consideration a feedback between the resource utilization of a given alternative, as assessed with the WELMM analysis, and its global cost. This might be very useful if the large-scale development of this alternative induced extensive utilization of some resources, which would increase its price. Let us take as an illustration the simple example of Table 2. A more detailed evaluation, through WELMM analysis, of the reference ceiling for cooling water would reveal the time at which cooling towers would become necessary, which means an increase in the capital costs of power plants. A similar example could be given for the land problems associated with solar power plants.

In multicriterion analysis*, the WELMM approach may enlarge the set of attributes traditionally considered; apart from economic, political and ecological attributes, it includes the resource requirements criteria. In such cases, WELMM should be viewed as part of a multicriterion analysis (Table 5).

Comparison of Energy Technologies: For a given activity within an energy chain, several competitive processes or technologies may exist: uranium enrichment, for instance, can be achieved through gaseous diffusion, ultracentrifugation, nozzle, laser. In such cases, WELMM could be helpful for the comparison of processes, especially when the economic information for them is insufficient and unequal.

A WELMM comparison of competing processes for oil recovery was started in Spring 1976.

Although practiced for many years on a small or experimental scale in various oil fields, tertiary or enhanced recovery is probably having a fresh start now because of higher oil prices. Many methods are being explored and used--steam cycling, steam injection, in situ combustion, CO_2 miscible, micellar surfactants, caustic soda--and more will probably come on line--ultrasonics, laser, etc. Most of them have strong WELMM implications: water production, energy accounting (thermal methods can use as much as one third of recovered oil), materials problems [16] (10 lb of sulfonates, 3 lb of alcohols, 1 lb of polymer for each bbl of oil recovered with enhanced water flooding). For all of them, the manpower problem is also acute.

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*See [4] for a more detailed discussion of this problem.

Table 5. Multiattribute analysis of energy strategies: examples of attributes to be considered, regionally or globally, according to data availability.

Resource requirements WELMM	Water Energy Land Materials Manpower
Ecological impacts	Air pollution Water pollution Solid waste Occupational health
Economic attributes	Cost of the final output Manpower (more detailed) Capital requirements, etc.
Other attributes	Technological dependence Primary resources dependence Safety (risk evaluation) Rigidity (the possibility of modifying a strategy being implemented) ...

Comparison of Competitive Energy Chains: The energy chains we will refer to are mainly alternative chains for the supply of a given energy market (electrical needs, heat needs in urban areas). In other words, the process comparison is extended to the comparison of a series of processes from primary energy extraction or collection to final energy use.

Because of the diversity of energy resources, the various activities do not necessarily run in the same order*. There is thus no standard format for the description of a chain. As examples of different levels of complexity, the nuclear electricity and solar electricity chains are described in Figure 7. The Jet Propulsion Laboratory has already made comparisons of electricity chains [18]: see for instance their results for two different chains, coal with lime scrubber flue gas desulfurization power plant, and uranium with the light water reactor (see Tables 6 and 7).

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*In the BNL Reference Energy System and Associated Data Bas [17], eight activities are systematically considered in the following order (when they occur): extraction, transportation, pro cessing, distribution, storage, conversion, electric generation, end uses. In the JPL Evaluation of Conventional Power Systems [18], as a result of a higher aggregation, only five steps are considered: harvesting, upgrading, transporting, conversion to electricity, management of final waste.

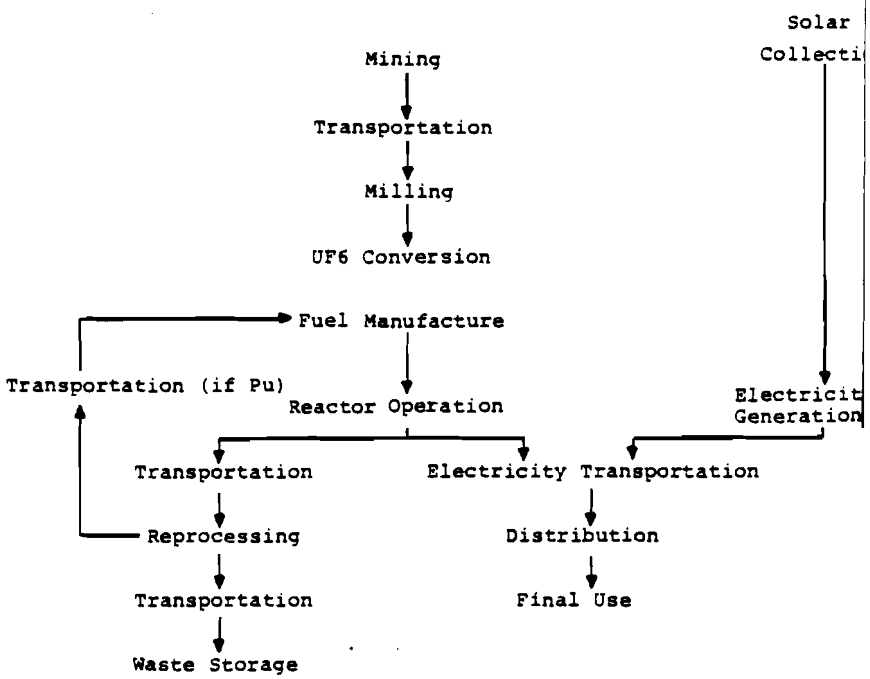

Figure 7. Nuclear and solar thermal electricity chains.

Table 6. Example of simple direct WELMM analysis for coal (Northern Appalachian, deep mined) with lime scrubber flue gas desulfurization and natural draft evaporative cooling tower [18].

Resource	Characteristics		Harvesting Fuels	Upgrading Fuels	Transporting Fuels	Conversion to Electricity	Management of Final Waste	Total
Water	10^3 m^3/MW(e)-yr		0	0.38	0	14.4	2.30	17.1
Energy	Primary Efficiency [%]		1.00	0.964	0.985	0.37	-	0.351 (net 0.344)
	Ancillary Consumption [MW(th-yr/MW(e)-yr]		$2.13\cdot10^{-2}$	$6.52\cdot10^{-3}$	$3.50\cdot10^{-2}$	0	-	$6.28\cdot10^{-2}$
Land	Temporarily committed [m^2/MW(e)-yr]	Disturbed	1500-3900	33.6	116	108	108	1900-4300
		Undisturbed	600-3000	-	233	-	-	800-3200
		Total	4500	33.6	349	108	108	4990
Materials	Construction	Metals	1.31	-	0.954	2.08	-	4.34
		Concrete	-	-	-	6.82	-	6.82
	Operation and Maintenance [t/MW(e)-yr]		-	-	-	247	-	247
Manpower	Construction (skilled)		46.71	-	21.14	376.8	-	444.6
	Operation and Maintenance [man-hours/MW(e)-yr]		1620	49.3	92.1	407	-	2170

Table 7. **Example of simple direct analysis for uranium (surface mined) with an LWR with natural draft evaporative cooling tower (plant efficiency 32%, capacity factor 75%) [18]. (Note the very low primary fuel efficiency related to the poor fuel utilization of the LWR.)**

Resource	Characteristics	Harvesting Fuels	Upgrading Fuels	Transporting Fuels	Conversion to Electricity	Reprocessing and Final Waste Management	Total
Water	(10^3 m^3/MW(e)-yr)	0.278	0.381	-	23	0.016	23.7
Energy	Primary Efficiency [%]	0.95	$7.04 \cdot 10^{-3}$	1.00	0.32	(included in upgrading)	$2.14 \cdot 10^{-3}$
	Ancillary Consumption [MW(th)-yr/MW(e)-yr]	$4.01 \cdot 10^{-3}$	0.126	$1.73 \cdot 10^{-5}$	-	$1.56 \cdot 10^{-4}$	0.13
Land	Temporarily committed: Disturbed	79.7	1.35	-	6.30	0.62	88.0
	Temporarily committed: Undisturbed	175	10.3	-	41.6	11.4	238.3
	Temporarily committed: Total	255	11.7	-	48.2	12.0	326.3
	Permanently committed [m^2/MW(e)-yr]	23.4	$9.2 \cdot 10^{-2}$	-	6.30	1.06	30.9
Materials	Construction: Metals [t/MW(e)-yr]	$5.58 \cdot 10^{-3}$	0.39	-	1.85	$8.25 \cdot 10^{-3}$	2.25
	Construction: Concrete [t/MW(e)-yr]	$1.83 \cdot 10^{-2}$	0.315	-	12.4	$6.59 \cdot 10^{-3}$	12.7
Manpower	Construction (skilled) [man-hours/MW(e)-yr]	2.53	15.21	-	518.10	6.52	542.4
	Operation and Maintenance [man-hours/MW(e)-yr]	115	90.1	-	250	31.2	486.3

As another application, we are trying to assess the WELMM requirements of alternative chains* for the supply of heat (space heat, hot water) in large urban centers with a high population density. A number of reasons justify this preliminary analysis:

- This market represents a significant fraction of the energy market in industrialized countries (about 30-40%);

- A wide range of technological possibilities (i.e. energy chains) exists that could be implemented to supply this market;

- In most industrialized countries, because of the urbanization process under development, more and more people are concentrated in large urban areas; as a result, the importance of this market can only increase.

Comparison of Regional or National Energy Strategies: Another application, possibly the most important, is a dynamic analysis and comparison of various energy strategies. The implementation of a given strategy will include a complete set of investments distributed over time:

- Direct investments in the activities of the energy chains, for which resource requirements can be assessed as above--for instance, for a nuclear strategy, the building of enrichment plants, fuel manufacture facility, nuclear reactors, preprocessing plants, transmission lines, etc.;

- Indirect investments,--induced by the direct investments, for extension of the production capacity of related industrial sectors--for which resource requirements can also be assessed as above. Using the same example, we can mention the extension of the production capacity of nuclear pressure vessels, steam generators, pumps, electric wires, etc.

Comparison of energy strategies requires a dynamic model of interrelations between these direct and indirect investments to assess the implications of a given strategy for an economic system. The industrial sectors affected by a strategy are the basic-materials industries, energy industries (where the direct investment takes place), capital goods and equipment industries (where the equipment used in energy industries is manufactured), machine tool industries (producing machine tools for manufacturing this equipment), and building and public works.

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*Geothermal, nuclear steam, hot water, nuclear or coal electric, coal or oil district heat.

At a given time, such relations can be quantified from industrial input-output tables; over a long-term period most of them change because of technological changes, implying that it is almost impossible to base a dynamic model on input-output relations. The fact that input-output tables deal only with developed technologies is another limitation to their use (nuclear, and especially solar and geothermal, are not included in existing input-output tables). Consequently, the best solution seems to be the quantification of relations through a combination of input-output methods and direct accounting. Input-output analysis should be used mostly to quantify relations at a second or third level (indirect resource requirements), where technological changes can have only a small influence on the resources balance.

The Siberian Power Institute, Irkutsk, has developed a model to evaluate the direct and indirect economic impacts of energy strategies: manpower, basic materials, and capital goods requirements. The WELMM approach is to be combined with the Irkutsk model for the assessment of indirect resource requirements.

The question can be raised how to compare two completely different types of energy deployment: highly centralized or mostly decentralized. This problem is obvious for solar, but also arises for nuclear (large nuclear power parks or decentralized smaller power plants) and for petroleum exploitation of remote super-giant deposits or intensive exploitation of what are called "small oil and gas fields" [6]).

Many arguments can be proposed pro or con large centralized or small disseminated energy facilities, such as efficiency and economy of scale versus transportation distribution costs, large variation in materials demand, etc. Using WELMM analysis can contribute to a better assessment of the factors and their possible limits or decreasing influence.

Figure 8 summarizes the integration of the WELMM approach in traditional methods of strategy comparisons.

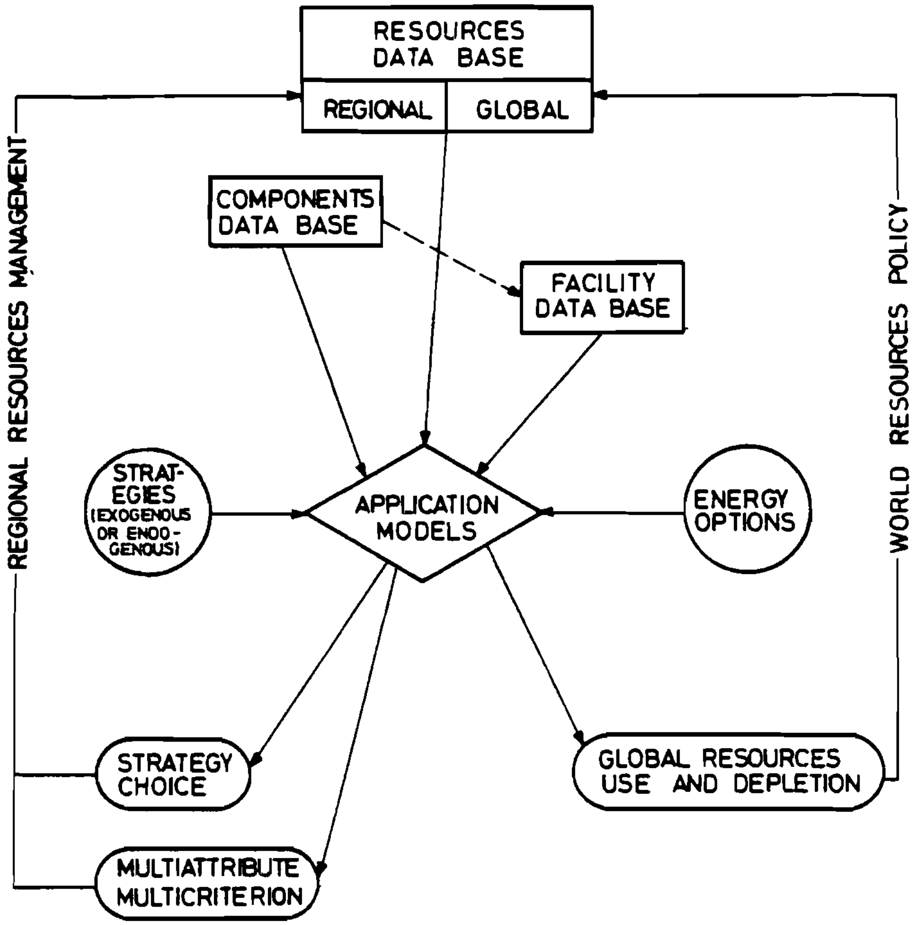

Figure 8. Application of the WELMM approach to the comparison of energy strategies.

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Appendix 1: Equipment Categories

1. Turbines (steam, gas, turbogenerator)
2. Electrical equipment
3. Construction, mining, and oil field equipment
4. Fabricated products (boiler, condenser, towers)
5. Material handling equipment (conveyors, cranes)
6. General equipment (pumps, valves, fans)
7. Instrumentation and control equipment
8. Transportation equipment
9. Miscellaneous equipment

Appendix 2: Basic File for the Components Data Base (CDB): Materials

(In this and the following appendices, for all data either the range of requirements or a figure denoting the hardness (i.e. confidence to be given to the data) is given. As in the Hittman studies [11], hardness ranges from 5 (hardest) to 1. More details can be found under the respective reference at the end of the file.)

MATERIALS	:	Aluminum, steel...
TECHNOLOGICAL CHAIN*	:	Description of the chain considered, from primary resource to materials, i.e. aluminum clay, ALCOA process
NATURE OF DATA	:	Global, national...
GENERAL COMMENTS	:	

*This data base indicates the cumulated requirements from natural resources to final materials.

W E L M M REQUIREMENTS FOR MATERIALS PRODUCTION
(PER TON OF MATERIAL)

		Extraction, Preparation, Concentration			Intermediate Products		
		Quantity	Hardness or Range	Ref.	Quantity	Hardness or Range	Ref.
WATER	INTAKE CONSUMPTION QUALITY						
ENERGY	ELECTRICAL FUEL						
LAND							
MANPOWER	TOTAL MAN-HOURS "CRITICAL" MAN-POWER (in %)						
MINERALS AND/OR BASIC MATERIALS							

Materials Production			First Transformation			Total		
Quantity	Hardness or Range	Ref.	Quantity	Hardness or Range	Ref.	Quantity	Hardness or Range	Ref.

Appendix 3: Basic File for the Components Data Base (CDB): Equipment

EQUIPMENT CATEGORY:		
CDB REFERENCE*	:	
SPECIFICATION	:	Capacity, lifetime and all useful technical specifications
NATURE OF DATA	:	Global, national...
COMMENTS	:	

*See Appendix 1.

W E L M M REQUIREMENTS FOR EQUIPMENT PRODUCTION*.

		Quantity	Hardness or Range	Ref.
ENERGY	ELECTRICAL FUEL			
MANPOWER	(MAN-HOURS)			
MATERIALS**	STEEL CONCRETE ALUMINUM . . .			

*Only the direct requirements at the level of the equipment production factory are included; the WELMM resources contained in the materials, not listed in the table, can be deduced from the Components Data Base for materials.

**Quantity of materials actually contained in the equipment.

Appendix 4: Basic File for the Facility Data Base (FDB)

FACILITY and PROCESS	:	e.g. district heating plant
PRIMARY INPUT	:	e.g. Northwestern coal
OUTPUT	:	e.g. steam
NATURE OF DATA	:	Global; national; specific (project of a certain town in the case of district heating)

Table 1. Equipment contained in the facility.

EQUIPMENT TYPE	Comments	Specific Cost**	CDB Ref.*

Comments:

*Cf. Appendix 1.

**Specific cost per unit of capacity ($/MW(e) or $/km of transmission lines).

Table 2. Materials requirements.

MATERIAL TYPE	CONSTRUCTION REQUIREMENTS					OPERATION REQUIREMENTS		
	Field Construction Materials			Equipment Production*	Total			
	Quantity	Hardness or Range	Ref.			Quantity	Hardness or Range	Ref.
Carbon steel (tons)								
Stainless steel								
Concrete								
....								
....								

Comments:

QUALITY CRITERIA

MATERIAL HANDLING — Review of main problems; Identification of major handling equipment.

WASTE PRODUCTION — Assessment of associated waste production.

RECYCLING POTENTIAL — General assessment, or, if available, detailed analysis of recycling potential for each material or group of materials.

MATERIALS ACCOUNTING

*Calculated from Table 1 and Appendix 3.

Table 3. Direct natural and human resource requirements for facility construction. (Construction time, capacity, capital cost, etc.)

Resource		Requirements for: On-Site Construction			Equipment Production*	Materials Production**	Total Quantity
		Quantity	Hardness or Range	Ref.	Quantity	Quantity	
WATER	INTAKE CONSUMPTION QUALITY						
ENERGY	ELECTRICAL FUEL						
LAND							
MANPOWER	TOTAL MAN-YEARS "CRITICAL" MANPOWER (in %)						
MATERIALS		***			***		***

Resource		Requirements for:					Total Quantity
		On-Site Construction			Equipment Production*	Materials Production**	
		Quantity	Hardness or Range	Ref.	Quantity	Quantity	
BASIC MINERALS	Iron Ore						
	Bauxite						
	. . .						

*From Table 1 Appendix 3.

**From Table 2 (col. 3) and Appendix 2.

***See Table 2.

Table 4. Direct natural and human resource requirements for facility operation. (Lifetime, annual primary input and energy output, primary and net efficiency, etc.)

Resource		Requirements for:				Total
		Facility Operation			Materials Production	
		Quantity	Hardness or Range	Ref.	Quantity	Quantity
WATER	INTAKE CONSUMPTION QUALITY					
ANCILLARY ENERGY	ELECTRICAL FUEL					
LAND	TEMPORARY USE — EXCL. / NON-EXCL. PERMANENT USE — EXCL. / NON-EXCL. CATEGORY					
MANPOWER	TOTAL MAN-YEARS "CRITICAL" MAN-POWER (in %)					

Resource		Requirements for:				Total
		Facility Operation			Materials Production*	
		Quantity	Hardness or Range	Ref.	Quantity	Quantity
BASIC MATERIALS	Iron Ore Bauxite . . .					

*Calculated from Table 2 (col. 4) and Appendix 2.