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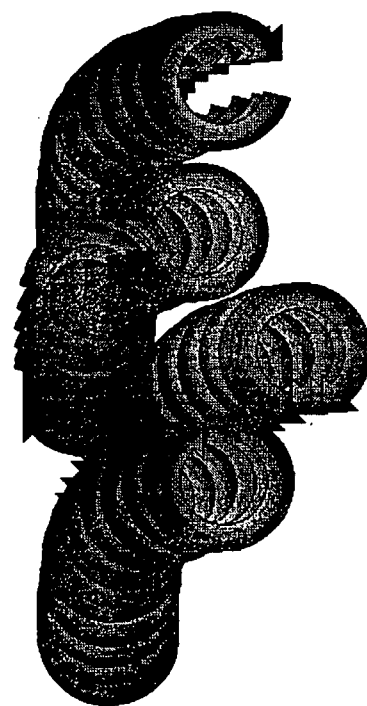
**LIFE-CYCLE ANALYSIS OF THE TOTAL  
DANISH ENERGY SYSTEM**

**an example of using methods developed for the  
OECD/IEA and the US/EU fuel cycle externality study**

**Bent Sørensen**

**February 1995**

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**LIFE-CYCLE ANALYSIS OF THE TOTAL DANISH ENERGY SYSTEM** An example of using methods developed for the OECD/IEA and the US/EU fuel cycle externality study.

by Bent Sørensen

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**ABSTRACT:**

This is the first annual report of the project "LIFE-CYCLE ANALYSIS OF THE TOTAL DANISH ENERGY SYSTEM - an example of using methods developed for the OECD/IEA and the US/EU fuel cycle externality study", which is a Danish companion project to the European Commission's project "ExternE" (External Costs of Fuel Cycles) under the JOULE II programme. The Danish project is financed by the energy research programme of the Danish Energy Agency. The aim of the project is to identify the state of art as regards life-cycle analysis of energy systems and to apply it to the current Danish energy system as well as to two scenarios for mid-21st century energy systems. The work in 1994 has concentrated on identifying the scenarios to be explored, and on collecting the externality data from the EU project and other sources, with a view to their applicability under Danish conditions. During 1995, it is expected that further impact data will be gathered, and that the scenarios will be tested by simulation models, in order to ascertain their internal consistency.

The present report begins with a brief outline of the work performed in 1994. Then follows an account of the life-cycle method and presentation of key results of externality studies abroad and in Denmark, with emphasis on the ExternE results. The first 9 reports from the ExternE study have been issued in a limited edition for a workshop held in Brussels late January 1995, with the participation of the IEA and the OECD. They will be commercially published later this year, along with further studies, including the Danish contribution, of which an internal progress report from June 1994 exists. The results presented here are for the coal, nuclear and wind cycles. Further completed reports exist for the oil and natural gas cycles, and the hydro and lignite cycles. The scenarios selected for the Danish application are presented in the second section of this report (in Danish), based on work performed for the Danish Technology Council and presented at its Conference on the RENEWABLE ENERGY SYSTEM OF THE FUTURE, held in the Danish Parliament Building November 1994. The scenarios were developed by a group of scientists from Roskilde University, Risø National Laboratory, Aalborg University and the Danish Energy Agency. The third section contains a conference paper from a presentation of the project at a conference in Beijing, organised by the Chinese Environmental Agency and IAEA. It contains an English language presentation of the renewable energy scenario of the Danish Technology Council.

# 1st Annual Report from the project

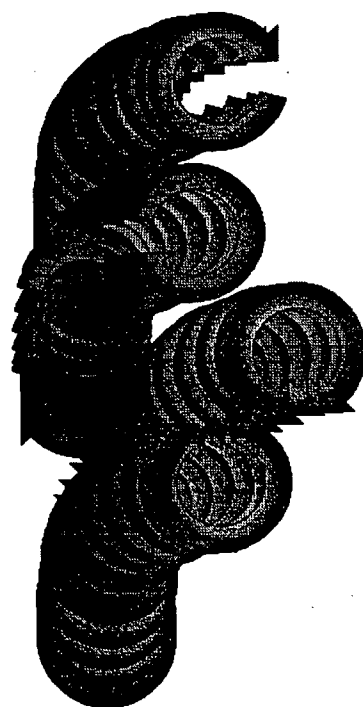
## LIFE-CYCLE ANALYSIS OF THE TOTAL DANISH ENERGY SYSTEM

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## PROJECT DEVELOPMENT AND STATUS

The European ExternE project, to which the Danish EFP project is linked, has progressed considerably during 1994. Most of the major fuel cycle studies have been completed, and the work in 1995 (the project runs to fall of 1995) will concentrate on getting the last studies finished (photovoltaic, end-use, buildings, biomass) and on discussing issues of how to aggregate from the site and technology specific studies to more generic results, that may be used as input to policy considerations. It is further expected, that some maintenance functions as well as the generalisation issues will be further pursued in a follow-up project under the fourth framework programme, along with further implementations in Europe and in Third World countries.

The ExternE study is a bottom-up approach, and it has greatly advanced the understanding of a number of externality issues. It has not invoked its own data collection, but has made a very detailed survey and critique of existing data, and thereby reached consensus on a number of problems encountered in the past. On the other hand, several impacts from the energy systems have still not been fully clarified, and the final documents from ExternE contain many items with "not quantified" or "too uncertain to allow adding up" warnings. Among the more spectacular "hanging issues" are the precise evaluation of greenhouse warming impacts, and a realistic appraisal of nuclear accidents, proliferation and waste handling issues.

The Danish implementation proposes to deal with the issue of greenhouse warming in some detail, which is made possible by Bent Sørensen's participation in the IPCC working groups. The following section will present some preliminary ideas in this area.

The Danish life-cycle study will as planned double its staff during 1995, hoping to progress considerably in all areas. The project will be wrapped up during 1996. In 1994, the emphasis has been on assessing work done by other groups, which in the case of impact assessment includes the Danish Risø-Technical University externality study of wind and biomass, the Dutch (Utrecht University), Australian (University of New South Wales) and UK (Northumbria University) work on photovoltaics, and the Japanese work (University of Tokyo) on all fuel cycles, in addition to the EU work. The Japanese work, which is linked to the IEA Scoping Study, has invoked Bent Sørensen as a consultant.

The other requirement was to identify energy scenarios suitable for performing life-cycle analysis for alternative energy systems contemplated for the middle of the next century. The choice made were two scenarios developed by the Danish Technology Council, by a project team including the main actors in the Danish life-cycle and externality field, including the project leader of the present project. This ensures, that underlying data are available and that the inner workings of the scenarios are accessible to the present project. One scenario is the likely development, taking into account trends already present in Danish public value systems, while the other involves a sharpened environmental concern, that could for example be induced by some visible effects of greenhouse warming, should they occur over the next couple of decades.

# **LIFE-CYCLE ANALYSIS, STATE OF THE ART**

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## **1. Introduction**

Life-cycle analysis is defined as an analysis of all impacts of a given product, technology or system, throughout its stages of life and including both direct impacts and indirect ones, e.g. from the materials and other inputs into the equipment used to manufacture, operate and dispose of the item discussed (Sørensen, 1993). In principle, the impacts are to be integrated over time and space, as far as they are still present. Impacts include direct and indirect, qualitative and quantitative impacts, enumerated for both the item under investigation itself and for the perhaps very long chain of inputs and inputs to inputs, where inputs are materials, energy, labour and equipment.

## **2. Description of the elements of an analysis**

The types of impacts that may be contemplated for assessment reflect to some extent the issues that at a given moment in time have been identified as important in a given society. It is therefore possible, that the list will be modified with time, and that some societies will add new concerns to the list. However, the following groups of impacts constitute a fairly comprehensive list of impacts considered in most studies made to date (Sørensen, 1993):

**\* Economic impacts such as impacts on owners economy and on national economy, including questions of foreign payments balance and employment.**

This group of impacts aim at the direct economy reflected in market prices and costs. All other impacts can be said to constitute indirect costs or externalities, the latter if they are not included in prices through e.g. environmental taxes. Economy is basically a way of allocating scarce resources. Applying economic assessment to an energy system, the different payment times of different expenses have to be taken into account, e.g. by discounting individual costs to present values. This again gives rise to different economic evaluations for an individual, an enterprise, a nation, and some imaginary global stake holder. One possible way of dealing with these issues is to apply different sets of interest rates for the above types of actors, and in some cases even a different interest rate for short-term costs and for long-term, inter-generational costs, for the same actor. Ingredients in these kinds of economic evaluation are the separate private economy and national economy accounts often made in the past. The national economy evaluation includes such factors as import fraction (balance of foreign payments), employment impact (i.e. distribution between labour and non-labour costs), and more subtle components such as regional economic impacts. Impact evaluations must pay particular attention to imports and exports, as many of the indirect impacts will often not be included in trade prices, or their presence or absence will be unknown.

**\* Environmental impacts, e.g. land use, noise, visual impact, local pollution of soil, water, air and biota, regional and global pollution and other impacts on the Earth-atmosphere system, such as climatic change.**

Environmental impacts include a very wide range of impacts on the natural environment, including both atmosphere, hydrosphere, lithosphere and biosphere, but usually with the human society left out (but to be included under the heading social impacts below). Impacts may be classified as local, regional and global. At the resource extraction stage, in addition to the impacts associated with extraction, there is the impact of resource depletion. In many evaluations, the resource efficiency issue of energy use in resource extraction is treated in conjunction with energy use further along the energy conversion chain, including energy used to manufacture and operate production equipment. The resulting figure is often expressed as an energy pay-back time, which is reasonable because the sole purpose of the system is to produce energy, and thus it would be unacceptable if energy inputs

exceeded outputs. In practise, the level of energy input over output that is acceptable depends on the overall cost, and should be adequately represented by the other impacts, which presumably would become large compared with the benefits, if energy inputs approached outputs. In other words, energy pay-back time is a secondary indicator, which should not itself be included in the assessment, when the primary indicators of positive and negative impacts are sufficiently well estimated. Also issues of the quality of the environment, as seen from an anthropogenic point of view, should be included here. They include noise, smell and visual impacts associated with the cycles in the energy activity. Other concerns could be the preservation of natural flora and fauna. It is normally necessary to distinguish between impacts on the natural ecosystems and those affecting human well-being or health. Although human societies are of course part of the natural ecosystem, it is convenient and often necessary to treat some impacts on human societies separately, which will be done in the following group. However, the situation is often, that a pollutant is first injected into the natural environment, and later finds its way to humans, e.g. by inhalation or through food and water. In such cases the evaluation of health impacts involves a number of calculation steps (dispersal, dose-response relation) that naturally have to be carried out in order.

**\* Social impacts, related to satisfaction of needs, impacts on health and work environment, risks, impact of large accidents.**

Social impacts include the impacts from using the energy provided, which means the positive impacts derived from services and products arising from the energy use (usually with other inputs as well), and the negative impacts associated with the energy end-use conversion. Furthermore, social impacts derive from each step in the energy production, conversion and transmission chain. Examples are health impacts, work environment, job satisfaction, and risk, including the risk of large accidents. It is often useful to distinguish between occupational impacts and impacts to the general public. Many of these impacts involve transfer of pollutants first to the general environment and then to human society, where each transfer requires separate investigation as stated above. This is true both for releases during normal operation of the facilities in question, and for accidents. Clearly, the accident part is a basic risk problem that involves estimating probabilities of accidental events of increasing magnitude.

**\* Security impacts, including both supply security and also safety against misuse, terror actions, etc.**

Security can be understood in different ways. One is supply security, and another the security of energy installations and materials, against theft, sabotage and hostage situations. Both are relevant in a life-cycle analysis of an energy system. Supply security is a very important issue, e.g. for energy systems depending on fuels unevenly spread over the planet. Indeed, some of the most threatening crises in energy supply have been related to supply security (1973/74 oil supply withdrawal, 1991 Gulf War).

**\* Resilience, i.e. sensitivity to system failures, planning uncertainties and future changes in criteria for impact assessment.**

Resilience is also a concept with two interpretations: One is the technical resilience, including fault resistance and parallelism, e.g. in providing more than one transmission route between important energy supply and use locations. Another is a more broadly defined resilience against planning errors (e.g. resulting from a misjudgment of resources, fuel price developments, or future demand development). A more tricky, self-referencing issue is resilience against errors in impact assessment, assuming that the impact assessment is used to make energy policy choices. All the resilience issues are connected to certain features of the system choice and layout, including modularity, unit size, and transmission strategy. The resilience questions may well be formulated in terms of risk.

**\* Development impacts (e.g. consistency of a product or a technology with the goals of a given society).**

Energy systems may exert an influence on the direction of development, a society will take, or rather may be compatible with one development goal and not with another goal. These could be goals of decentralization, goals of concentration on knowledge business rather than heavy industry, etc. For so-called developing countries, clear goals usually include satisfying basic needs, furthering education, and raising standards. Goals of industrialized nations are often more difficult to identify.

**\* Political impacts include e.g. impacts of control requirements, and on openness to decentralization in both physical and decision-making terms.**

There is a geopolitical dimension to the above issues: Development or political goals calling for import of fuels for energy may imply increased competition for scarce resources, an impact which may be evaluated in terms of increasing cost expectations, or in terms of increasing political unrest (more "energy wars"). The political issue also has a local component, pertaining to the freedom or lack of freedom of local societies to choose their own solutions, possibly different from the one selected by the neighbouring local areas.

### **3. Level of analysis**

Using in the remainder of the article the energy sector as an example, the different levels of analysis will be discussed. Consider first a single energy conversion device, placed at an identified site and employing a specific technology. Inputs are the materials and labour used to construct the device, say a power plant, and the inputs needed for operation and maintenance, including fuels if any, and finally the inputs needed for decommissioning and disposal or reuse/recycling of the constituents of the installation. The primary output from the device would typically be energy of a given form (or a service if it is an end-use device), plus associated outputs in the form of residues, emissions and nonphysical emissions. These outputs may affect the environment as well as human societies in different ways, which the assessment proposes to describe in terms of costs and benefits, quantified or not quantified, monetised or not.

The next level of analysis will try to embrace the entire fuel chain, i.e. extraction of fuels, refinement, transport and conversion, as well as the back-end of the conversion chain (spent fuel reprocessing, e.g. for nuclear fuels or ashes and tar from fossil power plants), and plant decommissioning. Fuel chain analyses rarely consider indirect impacts from energy and materials used in construction of e.g.



the power plant.

At the next level, the entire energy system of a given society is assessed, including transmission and end-use. In this case, the benefits can be taken as the final energy services, and indirect impacts everywhere in the system may be included. A possible exception is imports (say of fuels) or exports of energy, for which concrete analysis may not be possible. However, if this type of analysis aims at a full life-cycle treatment, then the origin of materials and equipment has to be traced back through society, which means that the ultimate analysis involves the entire (global) society.

This highest level of analysis includes all direct and indirect impacts, and therefore must include a model of society detailed enough to be able to trace impacts back to their origin, for materials and equipment. The simplest way of doing this would be through use of the input-output tables available in most countries, but of course the tables must be expressed in terms of physical quantities and not just monetary terms, because e.g. the environmental impacts of materials imbedded in certain equipment used in the energy industry will depend on the kind of materials involved (metals, composites, etc.), rather than on their cost. Again, this kind of assessment is made difficult, if many imports and exports are involved. The matrix methods associated with input-output analysis are useful tools in this type of calculation, but in most cases, the indirect impacts need to be traced back only a few steps, so that simpler methods can be used to give results within the overall uncertainty level, which is most often dominated by direct impacts rather than indirect ones. Certain renewable energy systems are exceptions, for which there are no significant direct impacts and where the indirect ones are hence dominating.

Figure 1 shows in a schematic form the global energy system, in which energy chains of the form illustrated in Figure 2 have to be analysed in terms of impact pathways for each step in the chain, as indicated in Figure 3.

#### **4. Pathway approach**

The impacts pertaining to a given step in the chain of energy conversions or transport may be divided into those characterising normal operation, and those arising in case of accidents. In reality, the borderline between often occurring problems during routine operation, mishaps of varying degree of seriousness, and accidents of different size are fairly hazy and may be described in terms of declining probability for various magnitudes of problems. The pathways of impact development are to a considerable extent similar for routine and accidental situations, involving injuries and other local effects, e.g. connected with ingestion or inhalation of pollutants, and as regards public impacts the release and dispersal of substances causing nuisance where they reach inhabited areas, croplands or recreational areas. The analysis of these transfers involves identifying all important pathways from the responsible component of the energy system, to the final recipient of the impact, such as a person developing illness or death, possibly with delays of considerable lapses of time, in cases such as late cancers.

Figure 3 shows how the pathway approach can be used to assess the direct impacts from a particular fuel cycle step. However, if the indirect effects are to be included in a full life-cycle analysis, then also inputs into the selected energy conversion step must be considered, whether they are materials,

equipment, energy, water or other types. In some cases there would be possible substitutions between human labour and machinery, linking the analysis to models of employment and reproductive activities. In order to find all the impacts, vital parts of the economic transactions of society have to be studied. For a given step in the energy conversion chain, one must consider all inputs to and outputs from a given device (i.e. a piece of conversion equipment, a transmission line or transport process, or an end-use device converting energy to a desired service or product). The relations between inputs and outputs of a given device may be highly non-linear, but in many cases given by a deterministic relationship. Exceptions are e.g. combined heat-and-power plants, where the same fuel input may be producing a range of different proportions of heat and electricity. This gives rise to an optimisation problem for the operator of the plant (who will have to consider fluctuating demands along with different dispatch options involving different costs). But for the actual mode of operation, the determination of inputs and outputs is of course unique. These are the numbers used in the impact assessment, which then has to trace where the inputs came from, and keep track of where the outputs are going. For each step, total impacts have to be determined, and in some cases the successive transfers may lead back to devices already considered. The way to deal with this problem is to set up all transfers between devices belonging to the energy system in a matrix. In what corresponds to an economic input-output model, the items associated with positive or negative impacts must be kept track of, such that all impacts belonging to the life-cycle will be covered.

Once this is done, the impact assessment itself involves integrations over time and space, or rather a determination of the distribution of impacts over time and space. The spatial part involves use of dispersal models or compartment transfer models (Sørensen, 1992), while the temporal part involves charting the presence of offensive agents (pollutants, global warming inducers, etc.) as function of time for each location, and further to determine the impacts (health impacts, global warming trends, and so on), with the associated additional time delays. This is conveniently done by considering the steps indicated in the pathway definition (cf. Figure 3). The result will be an impact profile in two dimensions, such as the ones emerging from the concrete examples in section 7 and briefly discussed in section 8.

### **5. Risk-related impacts and accident treatment**

Of the impacts presented below in section 7, clearly the accident related figures are parts of a risk analysis. As regards the health impacts associated with dispersal of air pollutants followed by ingestion and an application of a dose-response function describing processes in the human body, that may lead to illness or death, one can as mentioned in section 1 view these as processes governed by stochastic events, and thus suitable for inclusion in a risk assessment in the broad sense.

Probabilistic treatment of accident risks needs a few accompanying words. The standard risk assessment used in the airplane industry consist in applying fault tree analysis or event tree analysis to trace accident probabilities forward from initiating events or backward from final outcomes. The idea is that each step in the evaluation is a known failure type associated with a concrete piece of equipment, and that the probability for failure of such a component should be known from experience. The combined probability is thus the sum of products of partial event probabilities for each step along a series of identified pathways. It is important to realise, that the purpose of this evaluation is to improve design, by pointing out the areas where improved design is likely to pay off. Necessarily,

unanticipated event chains cannot be included. In areas such as airplane safety, one is aware that the total accident probability consists of one part made up by anticipated event trees, and one made up by unanticipated events. The purpose of the design efforts is clearly to make those accidents that can be predicted by the fault tree analysis (and thus may be said to constitute "built-in" weaknesses of design) small compared with the unanticipated accidents, for which no defense is possible, except to learn from actual experiences and hopefully move event chains including e.g. common mode failures from the "unanticipated" category into the "anticipated", where engineering design efforts may be addressed. This procedure has led to declining airplane accident rates, while the ratio between unanticipated and anticipated events has stayed at approximately the value 10.

It should of course be said, that the term "probability" is here used in a loose manner, as there is no proof of a common, underlying statistical distribution (Sørensen, 1979), due to constant technological change, making the empirical data different from the outcome of a large number of identical experiments. This is equally true, if we go to the cases of oil spills or nuclear accidents, for which the empirical data is weak, due to the low frequency of catastrophic events (albeit compounded with potentially large consequences). Here the term "probability" is really out of place, and if used should be construed to mean just "an indicator of a possible frequency of events".

The observed number of large accidents is for nuclear core-melt accidents two (Three Mile Island and Chernobyl), and for large oil spills similar or smaller. The implied "probability" in the nuclear case is illustrated in Table 1. Counting two accidents over the accumulated power production to the end of 1994 one gets a  $10^{-4}$  per TWh frequency, or a  $5 \times 10^{-5}$  per TWh frequency for an accident with severe external consequences. At the time of the Chernobyl accident, the estimate would have been 3-4 times higher, due to the much lower accumulated power production of reactors worldwide by 1986. For comparison, the built-in probability for an accident with Chernobyl-type consequences for a new, state-of-the-art light-water nuclear reactor is by the fault-tree analysis calculated to be about  $1.25 \times 10^{-6}$  per TWh (ST2-accident; Dreicer et al., 1995). The factor 40 difference between the two numbers comes partly from the difference between a state-of-the-art reactor and the average stock, and partly from the difference between the probability of anticipated accidents and the actual frequency, including unanticipated events. The latter should as mentioned contribute about a factor 10 according to sound engineering practices, and the former would thus be a factor of four. It is reassuring that the present risk assessments based on theoretical and on empirical methods thus have magnitudes that are basically understood, including the origin of differences.

## 6. Monetising issues

The use of common units for as many impacts as possible is of course aimed at facilitating the job of a decision-maker wanting to make a comparison between different systems. However, it is important that this procedure does not further marginalize those impacts that cannot be quantified, or which seems to resist monetising efforts. The basic question is really, whether or not the further uncertainty introduced by monetising offsets the value of being able to use common units.

Monetising may be accomplished by expressing damage in monetary terms, or by substituting the cost of reducing the emissions to some low threshold value (avoidance cost). Damage costs may be obtained from health impacts by counting hospitalization and workday salaries lost, replanting cost

of dead forests, restoration of historic buildings damaged by acid rain, and so on. Accidental death may e.g. be replaced by the insurance cost of a human life. Unavailability of data on monetising has led to the alternative philosophy of interviewing cross sections of affected population on the amount of money they would be willing to pay to avoid a specific impact or to monitor their actual investments (contingency evaluations such as hedonic pricing, revealed preferences, or willingness to pay). Such measures may change from day to day, depending on exposure to random bits of information (whether true or false), and also depend strongly on the income at the respondents' disposal, as well as competing expenses of perhaps more tangible nature. Should the statistical value of life (SVL) be reduced by the fraction of people actually taking out life insurance, or should it be allowed to take different values in societies of different affluence?

All of the methods introduced above are clearly deficient, the damage cost by not including a (political) weighing of different issues (e.g. weighing immediate impacts against impacts occurring in the future), the contingency evaluation by doing so on a wrong basis (influenced by people's knowledge of the issues, by their accessible assets, etc.). The best alternative may be to present the entire impact profile to decision-makers, in the original units and with a time-sequence indicating when each impact is believed to occur, and then to invite a true political debate on the proper weighing of the different issues.

A special role is played by problems of intergenerational equity, an issue that becomes relevant for many impacts from energy systems, due to delays between cause and effect, particularly in the case of nuclear energy. Several studies of monetised impacts use a discount rate to express the preference of having assets now rather than in the future. This preference is evident for individuals with a finite lifespan, but looking at national economies, the question arises, if assets left to future generations might not be exploited in a better way than present technology allows. The same may be true for liabilities, such as nuclear waste, that can be stored for later processing, whereas for air pollution the impacts are of course already committed at the time of ingestion. Most people would prefer a cancer occurring 20 years into the future to one now, but the question becomes more subtle if continuous suffering is involved. The intergenerational interest rate should basically be zero, placing the same value on the future as on the present. However, some would argue that we build up a stock of amenities for the future, which together with the technological progress enabling cheaper handling of deferred problems would point to a positive discount rate. On the other hand, knowledge regarding health and environmental impacts are likely to grow with time, making e.g. environmental standards likely to become more stringent in the future (continuing their development over the last couple of decades). Also new concerns are likely to emerge, all of which points to a negative discount rate. Because there is no way of telling precisely what the future societies will be concerned with, the most reasonable choice of an intergenerational discount rate in my view is zero.

### **7. Presentation of calculated impacts**

Based on recent studies of impacts, including both critical assessment of literature and in a few cases independent data collection, Tables 2-4 show the pathways employed and results obtained, for coal, nuclear, and wind technologies. This allows a comparison of the very different impact profiles of fuel-based and renewable energy systems.

The state-of-the-art coal-fired power plant considered in Table 2 is based on a proposed (but never built) plant located in England, with 99.7% particle removal. The quantified impacts are from a recent study performed under the EC Joule II Programme (ETSU and IER, 1995), except for the greenhouse warming impacts, which are estimated in Table 5 on the basis of work performed by the IPCC Working Group II for the second assessment report (IPCC, 1995). One of the central assumptions in the EC study is to monetise deaths using a value of a statistical life (SVL) amounting to 2.6 Mecu in all cases. If the value of life and health in developing countries were taken as zero, the global warming impacts estimated in Table 5 would diminish by a factor of 40. The impacts estimated in Table 5 are for the IPCC reference scenario assuming a doubling of greenhouse gases in the atmosphere by the middle of the 21st century, as compared with the pre-industrial level. However, the impacts themselves are accumulated over the 21st century, as many of them occur over a period of time. Power production using fossil fuels currently amounts to some 7000 TWh/y (all reference to TWh in the Tables refer to electric output) and is responsible for about 9% of greenhouse gas emissions. Thus the share of impacts may be taken as 70 Tecu. It is more difficult to express this per kWh, but assuming that the impacts are the result of 50 years of producing on average 10500 TWh/y (consistent with a doubling in 50 years), one obtains 0.13 ecu/kWh. This is the estimate used in Table 2 for the greenhouse warming impact.

The impacts of the coal fuel cycle is dominated by the global warming effects. However, the impacts associated with emissions are roughly a factor 10 lower than for an average British coal-fired plant, inferred from comparing the emission standard assumed here with typical emissions from current installations. In any case, many of the impacts presented in Table 2 are not quantified, so an assessment must deal with the qualitative impacts as well. In those cases where it has been feasible, uncertainties are indicated (L: low, within about a factor of two; M: medium, within an order of magnitude; and H: high, more than an order of magnitude), and the impacts are labelled according to whether they are local, regional or global (l, r or g), as well as whether they appear in the near term (n: under one year), medium term (m: 1-100 years) or distant term (d: over 100 years into the future).

A similar analysis of a state-of-the-art nuclear power plant is shown in Table 3, again based on the EC study (Dreicer et al, 1995) except for the impact of major accidents described in Table 1. The emphasis is on impacts from release of radioisotopes, and again monetising is involving a statistical value of life amounting to 2.6 Mecu, and a monetised value of hospitalisation equal to 6600 ecu, an emergency room visit set at 186 ecu, a work day lost at 62 ecu, bronchitis at 138 ecu, an asthma attack at 31 ecu, and a symptom-day at 6 ecu. The largest normal operation impacts are from the reprocessing step, but for deposition of high-level waste, no quantitative estimate was made of accidents that may occur over the required long deposition periods. Also the impact of proliferation of nuclear materials and know-how has not been quantified. The use of empirical data for the power plant large accident analysis may be criticised for not taking technological progress into account (cf. the discussion above on average and state-of-the-art technology). However, the present expansion of nuclear power takes place in developing countries, so it would seem prudent not to count on the higher standards of operational safety achieved in industrialized countries over the last decade. For example, reduction of impacts through early warnings, indoor confinement with controlled closure and opening of windows, evacuation and food bans is much less likely to function in developing countries. In fact, the early recognition of and public information on a problem, that is essential for

certain accident types, have not characterized the historic examples of accidents.

For a wind power plant, the similar impact evaluation presented in Table 4 (based on Meyer et al, 1994; Eyre, 1995) shows modest negative impacts, most of which occur during the construction phase, and substantial positive impacts in the area of impacts on the local and global society. The impacts during construction are to a large degree resulting from the use of fossil fuels in manufacture and transport, according to the marginal approach taken in the sources used. A comprehensive analysis of a renewable energy scenario would instead use the new energy system to determine indirect energy inputs, with substantially altered results as a consequence. Work along these lines are in progress within a project on life-cycle assessment of future energy scenarios for Denmark, carried out for the Danish Energy Agency. The slightly different spans in Figures 2-4 of benefits from selling the power produced are meant to reflect load-following capabilities of the different types of plants. For wind energy, there will be additional costs in case the penetration becomes large compared with the size of the grid system (say over 30%), because in that case additional equipment must be introduced to deal with the fluctuating power production of wind (Sørensen, 1995). The tabular impact values presented in Figures 2-4 may be presented as impact profiles for a multicriterion assessment.

#### **8. Discussion of calculated impacts and conclusions drawn**

The examples of section 7 indicate the level of analysis undertaken at present. It is evident, that each number to be provided requires large amounts of effort, and still cannot be given without substantial uncertainty. It is also clear, that the largest uncertainties are found for the most important impacts, such as nuclear accidents and greenhouse warming. Clearly there is a general need to improve data, by collecting information pertinent to these types of analysis. Even using national input-output data often discloses failure of statistical data to align with the needs of characterising transactions relevant for the energy sector. Also there are still a number of important impacts left as qualitative impacts. Some of these might be quantified, but if quantification and further monetising results in a large increase in the uncertainty, not much has been gained. It is one conclusion, that there still is an urgent need to be able to present qualitative and quantitative impacts to a decision-maker in such a way, that the weight and importance of each item become clear, despite uncertainties and possibly different units used. Some progress along these lines is in the construction of impact profiles (Sørensen, 1993; Sørensen and Watt, 1994), which can be labelled as a form of multivariate analysis and multicriteria decision-making.

The difficulties encountered in presenting the results of externality studies and life-cycle analyses in a form suited for the political decision-making process may be partly offset by the advantages of bringing into the debate the many impacts often disregarded (which is of course the core definition of "externalities", meaning issues not included in the market prices). It may be fair to say that life-cycle analysis and the imbedded risk assessments will hardly ever become a routine method of computerized assessment, but that they may continue to serve a useful purpose by focussing and sharpening the debate involved in any decision-making process, and hopefully help increase the quality of the basic information, upon which a final decision is taken, whether on starting to manufacture a given new product, or to arrange a sector of society (such as the energy sector) in one or another way.

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**Table 1. Frequency of and damage from large nuclear accidents**

Accumulated experience when Three Mile Island accident happened (1979)	3000 Twh
Accumulated experience when Chernobyl accident happened (1986)	5800 Twh
Accumulated experience to end of 1994	20000 Twh
Implied order of magnitude for frequency of core-melt accident	$1 \times 10^{-4} \text{ Twh}^{-1}$
* Implied order of magnitude for accident with Chernobyl-type releases	$5 \times 10^{-5} \text{ Twh}^{-1}$
Chernobyl:	
Dose commitment (UNSCEAR, 1993)	560000 man Sv
Induced cancers (SVL=2.6 Mecu, no discounting)	200 Gecu
Birth defects	20 Gecu
Emergency teams, clean-up teams, security teams	50 Mecu
Early radiation deaths (SVL=2.6 Mecu)	100 Mecu
Evacuation and relocation (cf. Dreicer et al, 1995)	100 Mecu
Food bans and restrictions (cf. Dreicer et al, 1995)	100 Mecu
Unplanned power purchases	1 Gecu
Capacity loss and reduced supply security	10 Gecu
Cost of encapsulation and clean-up (at plant and elsewhere)	170 Gecu
Increased decommissioning costs	100 Gecu
Impact on nuclear industry (reputation, reduced new orders)	100 Gecu
Monitoring, experts' and regulators' time	10 Mecu
Concerns in general public (psychosomatic impacts)	100 Mecu
<b>Total estimate of Chernobyl accident costs</b>	<b>600 Gecu</b>
<b>Industry average accident cost using *</b>	<b>30 mecu/kWh</b>

1 mecu = 0.125 US cents = 0.125 ¥

**Table 2. Impacts from coal fuel chain (state-of-the-art technology)**

<b>Environmental impacts</b>	<b>type of impact: emissions (g/kWh)</b>	<b>un- cer- tainty</b>	<b>monetised value mecu/kWh</b>	<b>uncer- tainty &amp; ranges*</b>
1. Plant construction/decommissioning	NA		NA	
2. Plant operation				
CO <sub>2</sub>	880	L		
SO <sub>2</sub> (may form aerosols)	1.1	M		
NO <sub>x</sub> (may form aerosols)	2.2	M		
particulates	0.16	M		
CH <sub>4</sub>	3	M		
N <sub>2</sub> O	0.5	H		
Greenhouse warming (cf. Table 5)	from CO <sub>2</sub> , CH <sub>4</sub> ,...		130	H,g,m
Degradation of building materials	from acid rain		1	H,r,n
Reduced crop yields	from acid rain		NQ	
Forest and ecosystem impacts			NQ	
Ozone impacts			NQ	
	cases:			
Mortality from particles (PM <sub>10</sub> )	1 per TWh	H	2.7	H,r,n
from aerosols	0.2 per TWh		0.5	H,r,n
from chronic effects	7 per TWh		NQ	
Morbidity from dust and aerosols,				
major acute	0.4 per Twh		0	M,r,n
minor acute	40000 work days lost/TWh		0.6	M,r,n
chronic cases	150 per TWh		0	M,r,m
Noise (from power plant)			0.1	M,l,n
<b>Occupational health and injury</b>				
1. Mining diseases			0.1	M,l,m
Mining accidents, death	0.1 per TWh		0.2	L,l,n
major injury	3.1 per TWh		0.4	L,l,n
minor injury	27 per TWh		0.1	H,l,n
2. Transport, death	0.02 per Twh		0.1	L,l,n
major injury	0.15 per Twh		0	M,l,n
minor injury	0.69 per TWh		0	H,l,n
3. Construction/decommissioning	0 per TWh		0	M,l,n
4. Operation	0 per TWh		0	L,l,n

<b>Economic impacts</b>				
Direct economy			25-45	
Resource use	low but finite		NQ	
Labour requirements			NQ	
Import fraction (UK plant)	local coal assumed		NQ	
Benefits from power			50-150	
<b>Other impacts</b>				
Supply security	many import options		NQ	
Robustness (against technical error, planning errors, assessment changes)	fairly low for large plants		NQ	
Global issues	competition		NQ	
Decentralisation and consumer choice	not possible		NQ	
Institution building	modest		NQ	

NA= not analysed, NQ= not quantified. Sources: ETSU& IER, 1995 and own estimates (cf. Table 5).  
 \* (L,M,H): low, medium and high uncertainty. (l,r,g): local, regional and global impact. (n,m,d): near, medium and distant time frame (cf. text).

**Figure 3. Impacts of nuclear fuel cycle**

<b>Environmental emissions</b>	dose commitment man Sv/TWh	un- cer- tainty	monetised value mecu/kWh	uncer- tainty & ranges*
CO <sub>2</sub> , SO <sub>2</sub> , NO <sub>x</sub> , particles	NA		NA	
Noise, smell, visual impact	NA		NA	
<b>Radioactivity</b>				
1. Fuel extraction and refinement	0.1	L	0.1	M,l,n
	0.1	L	0	M,r
	0	L	0	M,g
2. Normal power plant operation	0.4	M	0.1	M,l,m
	0	M	0	M,r
	1.9	M	0.3	M,g,d
3. Power plant accidents	5	H	2	H,l,m
	10	H	3	H,r,m
	15	H	5	H,g,d
4. Reprocessing and waste handling	0.2	H	0	H,l,d
	0	H	0	H,r,d
	10.2	H	1.9	H,g,d
<b>Social impacts</b>				
Occupational injuries	0		NQ	
Occupational radioactivity				
1. Fuel extraction and refinement	0.1	L	0	M
2. Construction and decommissioning	over 0.02	M	0	M
3. Transport	0	L	0	L
4. Normal power plant operation	0	M	0	M
5. Power plant accidents	0	M	0.003	H,l,n
6. Reprocessing and waste handling	0	H	0	H
Accident handling (evacuation, food ban, clean-up, monitoring, backup power, ...)			15	H,r,m
Indirect accident impacts (expert time, loss of confidence in industry, popular concern, ...)			5	H,g,m
<b>Economic impacts</b>				
Direct costs			30-50	L
Resource use	not sustain- able without breeders		NQ	
Labour requirements	low		NQ	
Import fraction (for France)	low		NQ	
Benefits from power (consumer price)			45-135	L

<b>Other impacts</b>				
Supply security	medium		NQ	
Robustness (technical, planning, assessment)	important		NQ	
Global issues (proliferation and weapons)	important		NQ	
Decentralization and choice	not possible		NQ	
Institutions building (safety and control)	fairly high		NQ	

Based on Dreicer et al, 1995; and own estimates, cf. Table 1. See notes to Table 2.

**Table 4. Impacts from wind energy systems**

<b>Environmental impacts</b>	<b>impact type: emissions (g/kWh)</b>	<b>un- cer- tainty</b>	<b>monetised value mecu/kWh</b>	<b>uncer- tainty &amp; ranges</b>
<b>Releases from fossil energy used:</b>				
1. Turbine manufacture (6.6 GJ/kW rated)				
CO <sub>2</sub> (leading to greenhouse effect)	12.1	L	1.8	H,g,m
SO <sub>2</sub> (leading to acid rain and aerosols)	0.05	L	0.1	H,r,n
NO <sub>x</sub> (possibly aerosols and health impacts)	0.04	L	0	H,r,n
particulates (lung diseases)	0.002	L	0.1	H,r,n
2. Operation (2.2 GJ/kW over 20 year lifetime)				
CO <sub>2</sub> (leading to greenhouse effect)	3.8	L	0.5	H,g,m
SO <sub>2</sub> (leading to acid rain and aerosols)	0.01	L	0	
NO <sub>x</sub> (possibly aerosols and health impacts)	0.02	L	0	
particulates (lung diseases)	0	L	0	
	other:			
Noise from gearbox at inhabited areas	<1 dB(A)		NQ	
from wind-blade interaction	<3 dB(A)		NQ	
Land use	10m <sup>2</sup> /kW		NQ	
<b>Social impacts</b>				
<b>Occupational injuries (manuf. &amp; materials):</b>				
1. Turbine manufacture, death	0.03/Twh	L	0	L,l,n
major injury	0.9/TWh	L	0.1	L,l,n
minor injury	5/TWh	M	0	M,l,n
2. Operation (same categories combined)			0	M,l,n
<b>Economic impacts</b>				
Direct costs			40-90	
Ressource use (energy payback time given)	1.1 y	L	NQ	
Labour requirements (manufacture)	9man y/MW	L	NQ	
Import fraction (for Denmark)	0.28	L	NQ	
Benefits from power sold (penetration < 30%)			40-120	
<b>Other impacts</b>				
Supply security (variability in wind is high, entry based on plant availability)	high		NQ	
Robustness (up-front investment binds, entry based on technical reliability)	high		NQ	
Global issues (non-exploiting)	compatible		NQ	
Decentralisation & choice (less with large size)	good		NQ	
Institution building (grid required)	modest		NQ	

Based on Meyer et al, 1994; Eyre, 1995; Sørensen, 1994. See notes to Table 2.

**Table 5. Estimated global warming impacts during 21st century for IPCC reference case.**

<b>Impact description:</b>	<b>Valuation (Tecu)</b>
Additional heatwave deaths (1M, valued at 2.5 Mecu each)	2.5
Fires due to additional dryspells	1.0
Loss of hardwood- and fuelwood-producing forests	3.0
Increase in skin-cancer due to UV radiation	2.5
Additional asthma and allergy cases	2.0
Financial impact of increase in extreme events	2.0
Additional crop pests and adaptation problems for new crops	2.0
Increase in insect attacks on livestock and humans	1.0
Increased death from starvation due to crop loss (100M deaths, the affected population being over 300M)	250.0
Deaths connected with migration caused by additional droughts or floods (100M deaths, the affected population being over 300M)	250.0
Increased mortality and morbidity due to malaria, schistosomiases, cholera, etc. (100M deaths, the affected population being over 1000M)	250.0
Other effects of sanitation and freshwater problems connected with droughts, floods and migration	25.0
<b>Total of valuated impacts</b>	<b>795.5</b>

Based on discussions in IPCC, 1995; valuation estimates made separately. Uncertainty is very high.

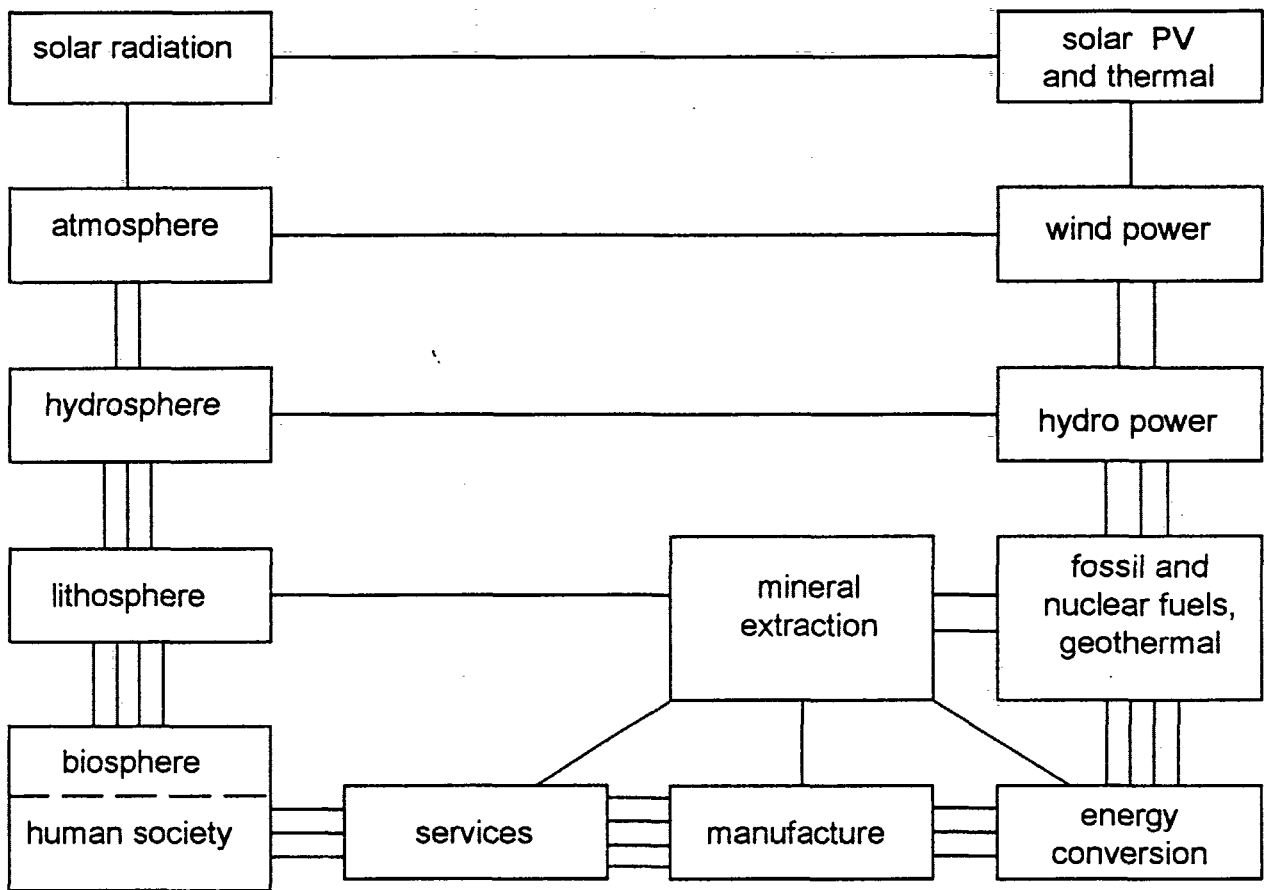


Figure 1. Overall structure of global energy system.



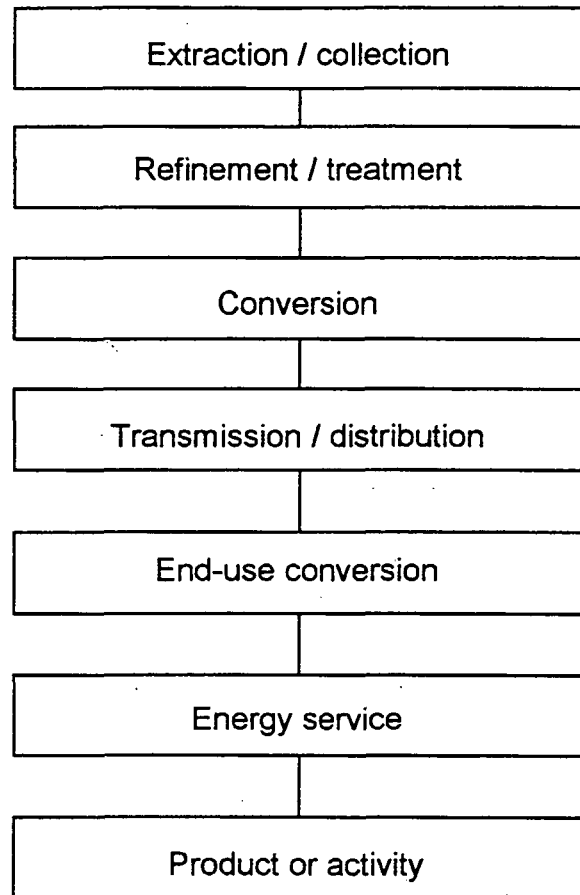
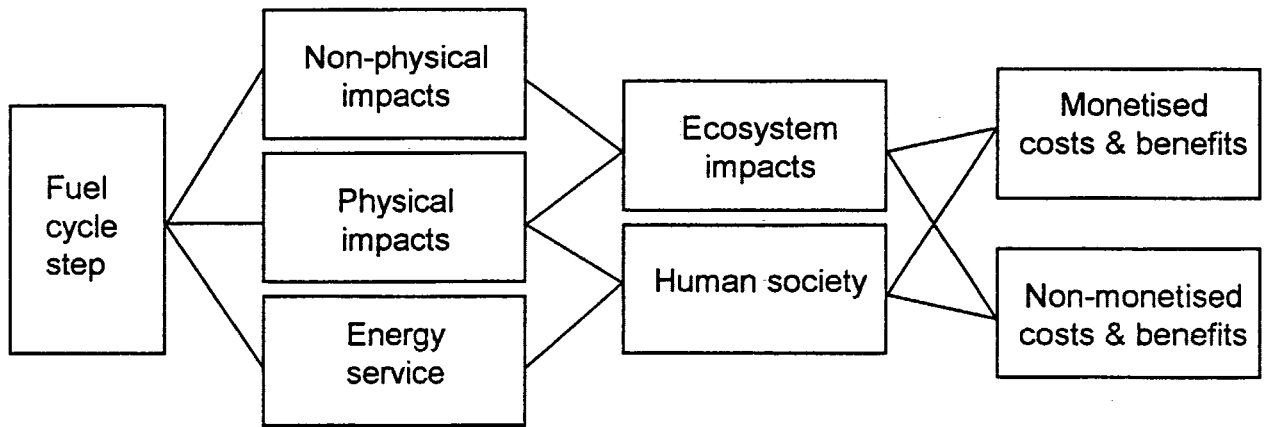


Figure 2. Energy conversion chain.



E.g.:  
 emissions → dispersal → level/concentration → dose-response → valuation → cost

Figure 3. Pathways for evaluating impacts.

Uddrag af

**FREMTIDENS  
VEDVARENDE  
ENERGISYSTEM**

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## Kapitel 4. Kvalitativ beskrivelse af scenarier for samfundsudviklingen med særligt henblik på energisystemet

Scenarier for fremtidens samfund vil her primært blive skitseret for så vidt angår arten af energiforbrugende teknikker. Om samfundet iøvrigt er baseret på højteknologi, mange serviceydelser, fritidsaktiviteter eller informationsteknologier er i denne sammenhæng kun interessant, for så vidt som det influerer på energiforbruget.

Udviklingen indenfor elektronik har medført en meget betydelig sænkning af energiforbruget per apparat, påkrævet simpelthen fordi miniaturiseringen gør, at varmeudvikling ikke kan accepteres, og energiforbruget skal derfor være så lille som muligt. Men det kræver et scenarie for samfundsudviklingen at afgøre, om nedsættelsen af energiforbrug per enhed overskygges af et stigende antal enheder eller ej.

Vi har valgt to scenarier, som afspejler en videreførelse af tendenser, der allerede kan observeres: Større miljøbevidsthed, valg af samværsformer hvor de menneskelige aspekter er mere væsentlige end brug af teknik. De to scenarier kan ses som efterfølgende hinanden i tid, eller som en godt 30 års udvikling med to forskellige hastigheder. Et lysegrønt scenarie på kortere sigt, et mørkegrønt på længere sigt, eller et fortløbende der med tiden melder den grønne farve klarere ud.

Naturligvis udspænder sådanne to scenarier ikke hele mulighedsrummet. På den ene fløj er der folk som mener, at vi bliver trætte af det materielle samfund og vil søge mod enklere, mindre forbrugende samfund. På den anden fløj finder vi dem, der blæser på miljøet og siger at det væsentlige er at forbruge mere og hurtigere. Vi tror at det er i overensstemmelse med dansk tankegang at vælge en mellemløsning og så håbe på, at også dem på fløjene kan finde sig tilrette i et sådant samfund.

Dette er tankegangen bag de to scenarier, som begge antager en udvikling i forbrug og aktiviteter, som antager andre former end idag, måske "vokser" eller repræsenterer en fremdrift, men ikke antager umådeholdende proportioner. At samfundet ikke er statisk, kan næppe nogen benægte. De seneste årtier har været vidne til en hastig ændring af vores samfund på næsten alle områder. At antage, at ændringerne pludselig skulle holde

op og alt svare til en "business as usual", er nok den mest usandsynlige forestilling man kan have om fremtiden.

Afgørende for opstillingen af et energi-scenarie har for os været miljøsyn, som vi mener vil diktere anvendelsen af vedvarende energikilder i langt større omfang end nu. Men afgørende for en rationel anvendelse af vedvarende energikilder er den samlede efterspørgsel efter energi. Antallet og arten af vedvarende energiløsninger er særdeles afhængig af energiforbrugets størrelse i forhold til solindfald, vindoverstrygning, osv. Op til et vist niveau kan løsninger baseret helt på vedvarende energi være fordelagtige, mens dækning af et endnu større energiforbrug med vedvarende energikilder kan vise sig at indebære stejlt stigende priser, således at ikke-vedvarende energikilder må komme på tale som supplerende, trods øgede miljøomkostninger.

Det er denne rapport's mål at indkredse det niveau af energiforbrug, som optimalt kan dækkes af vedvarende energi. Afgørende i denne forbindelse er afgrænsningen af planlægningsområder; byområder og åbne landområder har forskellige potentialer for udnyttelse af vedvarende energi, ligesom forskellige geografiske forhold indebærer forskellige ressourcefordelinger. Herved bliver planlægningsgrænserne afgørende: Skal planlægningen ske for lokale områder, skal løsningerne være decentrale eller indeholde forskellige grader af centralisering, skal der kunne udveksles energi mellem områderne, enten ledningsbunden (f.eks. el, fjernvarme, biogas eller brint) eller transportérbar energi (f.eks. biomasse, biobrændsler)?

Tilstedeværelsen af transmissionssystemer gør det lettere at designe et optimalt energisystem med stor forsyningssikkerhed, men omkostningerne ved at anlægge transmissionsnettet skal naturligvis indgå i overvejelserne, hvis det ikke allerede findes.

Vi vil undersøge disse forhold gennem vore to scenarier, og vi vil give et skøn over de vedvarende energiresources mængde og fordeling, som kan indgå i vurderingen af forskellige forslag til systemopbygning. Der bliver præsenteret mere dokumentationsmateriale for det mørkegrønne scenarie, simpelthen fordi det indeholder flere tanker, der er nye og kræver uddybning. Det lysegrønne scenarie forudsætter effektivisering af energiforbruget i boliger og andre bygninger, men i mindre grad industriens energiforbrug og forbruget til transport.

Det mørkegrønne scenarie forsøger at sætte lige kraftigt ind i alle sektorer af samfundet. Heraf følger også, at det lysegrønne scenarie kun formår at dække en del af energiforbruget med vedvarende energi, og må bevare de fossile brændsler i et ikke helt lille omfang. Dette betyder så til gengæld, at der er færre problemer med indpasningen af de vedvarende energikilder med deres særlige tidsbundethed.

I det mørkegrønne scenarie er det samlede energiforbrug lavt nok til, at vi kan dække det med indenlandske vedvarende energikilder. Til gengæld må det skrues sammen med meget stor omhu, for at de vedvarende energikilder der ikke kan reguleres, kan komme ind uden at bringe forsyningssikkerheden i fare. Vi har derfor brugt en del kræfter på at gennemtænke systemets funktion i praksis, omend det i samme åndedrag må siges, at den foreliggende undersøgelse er preliminær, og at der kræves en god del mere arbejde, før nogen af os ville kunne anbefale direkte overførsel af scenarierne fra tegnebrættet til den danske energipolitiks grundlag.

#### **4.1 Et lysegrønt scenarie for Danmark år 2030**

Scenariet udspilles år 2030. I forhold til i dag er samfundet karakteriseret ved en stor energi- og miljøbevidsthed, både på lokalt, nationalt og globalt plan.

I løbet af 1990'erne og starten af 2000-tallet er det blevet klart, at væsentlige miljøtiltag er nødvendige, hvis mennesket skal overleve på jorden. Væsentlige klimaændringer er på vej - jordens gennemsnitlige middeltemperatur fortsætter med at stige, hvilket medfører regionale klimaforskydninger, opståen af tørke, voldsomme storme m.v. Den menneskeskabte drivhuseffekt må betragtes som en realitet, og specielt i den vestlige verden bliver der startet en række tiltag for at mindske udslippet af drivhusgasser.

Væsentlige lokale/nationale forureninger er mindsket i løbet af 1990'erne. Emissioner af  $\text{SO}_2$  og  $\text{NO}_x$  er i begyndelsen af 2000-tallet ved hjælp af installation af rensningsteknologier og brug af renere brændsler blevet bragt så langt ned, at de ikke længere opfattes som et miljøproblem. Til gengæld er der andre lokale emissioner, der er kommet i fokus, og til trods for løbende forbedringer af rensningsforanstaltninger synes den fortsatte afbrænding af fossile brændsler (og til en vis grad af biomasse) fortsat at skabe nye lokale/nationale miljøproblemer.

De generelle miljøproblemer har fået høj prioritet i samfundets udvikling, men ikke ændret udviklingen i markant grad bort fra velfærdssamfundet, som defineret i 1980'erne og 1990'erne. Problemerne er forsøgt taklet gennem indførelse af rensningsforanstaltninger, besparelser i energiforbruget og omlægning af energisystemet mod vedvarende energi og højeffektive anlæg. Udviklingen i samfundets materielle produktion og behov er vokset i moderat grad (væksten i bruttonationalproduktet er forudsat at være 1-1.5 pct. pr. år) og er således ikke voldsomt påvirket af miljøproblemerne. Selv ved denne ikke ubetydelige vækst synes det dog muligt for samfundet at reducere forureningen markant.

I år 2030 kan energi- og miljøpolitikken kort karakteriseres ved:

- Der er for den vestlige verden indført kvoter på CO<sub>2</sub>-udslippet. For Danmark udgør kvoten 40 pct. af udslippet i 1992.
- I EU-regi er der indført markante miljøafgifter, ikke kun på CO<sub>2</sub>, men ligeledes på lokale/nationale emissioner for at afspejle miljøbelastningen ved disse stoffer.
- Der er indført normer og standarder for apparater og maskiner for såvel husholdninger, service og industri.
- Danmark er forpligtet af en række yderligere internationale ordninger og aftaler på energi- og miljøområdet.

Energisystemet er opbygget over en hovedsagelig central struktur med stor anvendelse af naturgas og kraftvarme. I forhold til 1992 er der gennemført væsentlige energibesparelser, men primært ved anvendelse af mere effektive teknologier og ikke i gennemsnit ved omlægning af forbrugeradfærden. Sidstnævnte dækker dog over store variationer i forbrugernes adfærd med hensyn til energibesparelser.

## **4.2 Et mørkegrønt scenarie for Danmark år 2030**

Dette scenarie forudsætter, at de fossile brændsler udfases helt. Det kan enten ske i forlængelse af det lysegrønne scenarie, eller kan som her forudsat fremskyndes, f.eks. hvis uforudsete globale begivenheder overbeviser danskerne om, at udfasningen af

drivhusgas-udsendende energiformer må ske hurtigere end tidligere antaget, eller simpelthen fordi bevidstheden om det nuværende, fossilt baserede energisystems skadelige "eksternaliteter" (dvs. omkostninger som ikke reflekteres i dagsprisen) højnes i løbet af de næste tiår.

Scenariet bygger på stort set samme niveau af energiserviceydelser som det lysegrønne scenarie, men der forudsættes en langt større indsats for at forbedre energiomsætningernes effektivitet, såvel som valg af de mest hensigtsmæssige metoder til at levere de ønskede sluttjenester og produkter.

Det er ikke tanken at bruge meget tid på at beskrive begivenheder, som kunne fremtvinge en haste-indsats for at fjerne de fossile energikilder, da det forudsættes at begivenheden er uforudset. Vi vil imidlertid kort skitsere et eksempel på en sådan begivenhed, for at give fremstillingen et mere realistisk præg:

Omkring år 2000 sker der en række dramatiske klimaændringer, der overbeviser politikere over hele verden om, at den menneskeskabte drivhuseffekt er reel og muligvis værre end mange af de foreliggende videnskabelige beregninger. Disse har hele tiden angivet en betydelig usikkerhed, som dels skyldes modellernes begrænsninger, og dels at menneskesamfundet foretager mange andre indgreb i klimaet, hvis samspil med drivhuseffekten ikke kendes i detaljer.

Jordens middeltemperatur ændrer sig godtnok kun med et par grader, hvilket på kort sigt drukner i variationer fra år til år, men der sker dramatiske ting med nedbør og vindforhold. Udsvingene bliver større, stabiliteten mindre. Katastrofeagtige oversvømmelser sker hyppigere og hyppigere; forsikringsselskaberne opgiver at yde erstatninger i sådanne tilfælde. Det erindres at menneskets aktiviteter tidligere har udvirket klimaændringer, som f.eks. skovfældning og afbrænding ("slash and burn"), der antages at have skabt ørkener som Sahara og Rajputana, den sidste for kun ca. 1000 år siden.<sup>3</sup>

En tørke som fornyligt set i Sahel-området antages nu at brede sig med stor hast over sletterne i Nordamerika, og det brede landbrugsbælte omdannes hurtigt til gold ørken. Det samme sker i Europa, omend i et mere broget mønster. Andre områder får mere

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<sup>3</sup> Sørensen, 1979.



regn, f.eks. den nordlige del af Centralasien, og der gøres et forsøg på at henlægge kornproduktion i stor stil til disse områder. Forsøget slår imidlertid fejl, da det viser sig, at den tidligere Sovjetiske jord er så forurennet, at afgrøderne ikke blot byder på store helbredsrisici, men også at de gængse kornsorter faktisk ikke kan overleve, på grund af angreb af svampe, parasitter osv., hvor balancen af modstandskraft mellem afgrøde og skadedyr synes forrykket til fordel for skadedyrene. Der synes måske at være en løsning på vej, med øget kornimport fra Sydamerika og Australien, som ser ud til at have fået et gunstigere klima i de indre egne.

Imidlertid skabes der international enighed om, at brugen af fossile brændsler må ophøre totalt over en 20-30 års periode, for at bremse de fortsatte klimændringer, så indsatsen kan rettes mod overlevelse under de nye omstændigheder. Alverdens lande er derfor optaget af en debat om, hvilken form for energiømlægning der bedst kan klare dette problem. En række lande mener at kernekraft er løsningen; ikke mindst fordi de selv kan producere og eksportere anlæg.

Imidlertid taler de uløste problemer med store ulykker og affaldsbehandling imod atomkraftløsningen, ligesom den igangværende demontering af kernevåben vil kunne forløbe mere sikkert, hvis der ikke opstår nye lande med tvivlsom kombination af civile og militære interesser i kernekraft. Endelig påpeger forskerne, at en indsats indenfor energieffektivisering vil give de hurtigste resultater.

Den danske regering beslutter sig som en af de første for en model, der bygger på hurtig forbedring af energiudnyttelsen, kombineret med en kraftig udbygning af vedvarende energisystemer, hvor Danmark allerede er teknologisk blandt de førende lande. Hungerkatastroferne, som dagligt fylder avisernes forsider, gør at gennemførelsen af den nye energiplan ikke møder modstand i befolkningen, som er positivt indstillet overfor de tiltag, der sker, og selv arbejder med i omlægningen af den danske industripolitik, gennem en periode hvor meget store ressourcer dedikeres til energiømlægningen.

Den danske velstand er jo netop funderet i at være forud for andre lande med denne type nytænkning (f.eks. har danske fabrikker herved kunnet være næsten alene på vindkraftmarkedet i henved 20 år). Det er jo også en kendt ting, at udefra kommende pludselige begivenheder ofte medfører holdningsmæssige retningsændringer som ellers ville være utænelige. Dansk energihistorie rummer adskillige eksempler herpå.

Imidlertid er det mørkegrønne scenarie ikke afhængigt af, at der skal ske en klimakatastrofe. Den holdningsmæssige udvikling mod større respekt for miljø og naturressourcer trækker i samme retning. Endelig kan en økonomisk analyse vise, at dette i alle

tilfælde er den billigste løsning, set i et livscyklus-økonomisk perspektiv. I en sådan analyse vil de fossile løsninger blive meget dyre pga. miljøpåvirkningerne, således at den rigtige balance mellem de også dyre vedvarende energiløsninger og foranstaltninger på energiforbrugssiden kan tænkes forskudt i retning af større investeringer i effektivitet, og dermed et mindre behov for anvendelse af (dyr) energi.

I afsnit 5.3 og 6.3 beskrives forbrugsantagelserne og systemopbygningen i det mørkegrønne scenarie for det energisystem, scenariet styrer imod at opbygge før år 2030.

## Kapitel 5. Scenarier for efterspørgslen efter energi

### 5.1 Energiefterspørgslen i dag

Det samlede netto- og endelige energiforbrug i Danmark i 1992 er angivet i tabel 5.1.

Tabel 5.1. Netto- og endeligt energiforbrug i 1992.

	1992			
	Endeligt energiforbrug		Nettoenergiforbrug	
	PJ	pct.	PJ	pct.
Opvarmning	199	34	162	31
- heraf el	9	-	9	-
Apparater (el)	44	7	44	8
Køling (el)	15	3	15	3
Proces	152	26	132	35
- heraf el	41	-	41	-
Transport	174	30	174	33
- heraf el	1	-	1	-
I alt	584	100	527	100
- heraf el	110	-	110	-

Kilde: Energistyrelsen og Risø.

Procesenergi omfatter energiforbruget til industri, landbrug og gartneri, samt bygge- og anlæg.

Det endelige energiforbrug adskiller sig fra nettoenergiforbruget ved at indeholde de lokale konverteringstab, eksempelvis ved anvendelsen af olie- og naturgasfyr i individuelle huse.

Det endelige energiforbrug er opgjort ud fra statistiske data - nettoenergiforbruget beregnes herefter ved antagelse af lokale tab.

For anvendelsen af el og for transportenergiforbruget er der ikke skelnet mellem netto- og endeligt energiforbrug.

Som det fremgår af tabel 5.1, går de mest betydende forbrug til opvarmning, transport og proces. Knap 20 pct. af det samlede forbrug går til elanvendelser.

## 5.2 Et lysegrønt scenarie for energiforbruget

Tabel 5.2 viser det beregnede nettoenergiforbrug år 2030 som følge af det ovenfor beskrevne lysegrønne scenarie.

*Tabel 5.2. Nettoenergiforbruget i dag samt i det lysegrønne scenarie.*

	1992 PJ	2030 PJ	Stigning pct. pr. år
Opvarmning	162	101	-1.2
- heraf el	9	4	-2.1
Apparater (el)	44	41	-0.2
Køling (el)	15	13	-0.4
Proces	132	134	0
- heraf el	41	49	0.5
Transport	174	160	-0.2
- heraf el	1	9	6.0
I alt	527	449	-0.4
- heraf el	110	116	0.1

Nedenfor forklares udviklingen i energiforbruget i de enkelte sektorer.

### **Procesenergi**

Den samlede mængde af varer er forudsat at stige ca. 80 pct. i forhold til i dag. Samtidigt indføres der væsentlige energibesparende foranstaltninger, således at energiforbruget til proces stort set er det samme i år 2030 som i dag, jvf. tabel 5.2. Energibesparelser gennemføres mest markant for olie, kul og naturgas, mens der stadig er en moderat stigning i elforbruget.

### **Opvarmning i boliger og service**

Folketallet stiger kun svagt frem til år 2030. Da den gennemsnitlige husstandsstørrelse falder ca. 30 pct. (bl.a. på grund af gode økonomiske forhold), bliver der alligevel bygget ca. 20.000 nye boliger om året fra 1992 til år 2030. I såvel nybyggeri som eksisterende bygninger satses der markant på isoleringsmæssige forbedringer, bl.a. gennem en stramning af bolig- og byggereglementet og gennem indførelse af højere miljøafgifter. Der forudsættes en høj tilslutningsgrad til kollektive net, såvel fjernvarme som naturgas, og restområdet med oliefyr reduceres betydeligt. Nettoenergiforbruget falder markant i forhold til i dag, jvf. tabel 5.2.

### **Elforbrug til apparater i bolig og service**

Som følge af den økonomiske udvikling øges bestanden af elapparater, specielt i servicesektoren. Anvendelse af apparaterne er antaget at være som i dag. Der gennemføres store besparelser for elapparater i såvel bolig som service. For husholdningsapparater reduceres forbruget til ca. 1/3 af det i dag værende gennemsnitsforbrug. Til trods herfor reduceres elforbrug til apparater kun moderat (jvf. tabel 5.2), hvilket hovedsageligt skyldes et øget forbrug i servicesektoren (handel, distribution, liberale erhverv, offentlige institutioner m.m).

### **Transport**

Det samlede transportbehov er forudsat at stige med 1-1.5 pct. p.a., stort set følgende den økonomiske udvikling. Effektiviteten i transporten stiger væsentligt. Til trods herfor er der kun en moderat reduktion i energiforbruget til transport på ca. 10 pct. i forhold til 1992. Energiforbruget til transport er forudsat hovedsageligt at blive dækket af fossile brændsler (olie), dog er der en moderat anvendelse af elbiler. Det er i dette scenarie valgt at anvende biomasse i kraftvarmesektoren, men anvendelse i transportsektoren kunne have været lige så relevant.

Det samlede forbrug på behovssiden er vist i tabel 5.2. Nettoenergiforbruget inkluderer ingen konverteringstab.

### **5.3 Et mørkegrønt scenarie for slutbrugernes energifterspørgsel i Danmark år 2030.**

Energiforbruget hos slutbrugere er opbygget nedefra og op, en metode der vides at give bedre resultater end prognosemageri på grundlag af historiske data. Det har derfor været nødvendigt at inddele de aktiviteter i samfundet, som indebærer energiforbrug, på en lidt anden og mere detaljeret måde, end det idag sker i dansk statistik. Som støtte til denne inddeling tjener specifikke undersøgelser samt energidata for lande, f.eks. USA, hvis statistiske materiale allerede tillader en sådan opdeling.<sup>4</sup>

Opdelingen i energiforbrugende aktiviteter bygger på en behovsmodel, som er udformet så den dækker alle samfundstyper fra tidlige udviklingsstadier til højt industrialiserede og vidensbaserede samfund.<sup>5</sup> Den spænder fra grundlæggende behov for mad, bolig, sikkerhed og helbred til behov for samvær og aktiviteter, omfattende også de aktiviteter der sigter mod at fremstille de varer og tjenester, som kræves af de nævnte typer af behovstilfredsstillelse.

En sammenfatning af behovene fremgår af figur 5.1, som også giver et bud på de energimængder, der med kendt teknologi tillader fuld behovsdækning. Disse tal er basis for år 2030 scenariet, som forestiller sig en videreførelse af tendenser, der allerede ses idag, i retning mod et mere videns- og informationsbaseret samfund. Dette medfører en stigning i aktiviteter relateret til vidensbaserede forretningsområder, informationsudveksling, kreative udfoldelser og "underholdning", altså især elektroniske, energiforbrugende apparater. Der er en global arbejdsdeling som vi allerede kender den idag. Vareproduktion og transport forbundet med distribution forudsættes at dække alle relevante behov. Imidlertid er energiforbruget til disse aktiviteter optimeret ved stor vægt lagt på effektivitet.

Figur 5.1 er udformet som en matrix, hvor arten af energiforbrugende aktivitet er beskrevet ned langs venstre side, mens overskrifterne på tværs angiver den påkrævede energikvalitet: varme ved lavere eller højere temperaturer, mekanisk eller elektrisk energi i stationære eller mobile (transport-) situationer, og endelig energi i fødevarer,

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<sup>4</sup> Sørensen, 1982.

<sup>5</sup> Sørensen, 1981c, 1984, 1988

der naturligvis skal med i samme åndedræt som energi til at holde vind og kulde fra livet i boliger og andre bygninger.

Energikvaliteter har en grundlæggende betydning for den tekniske udformning af energisystemer, fordi de lave kvaliteter (varme ved lav temperatur) kun med betydelige tab kan omdannes til højkvalitetsenergi, mens højkvalitetsenergi (mekanisk, elektrisk og kemisk energi) i princippet kan omdannes tabsfrit til enhver anden energiform. Omend detaljerne i energiomformningssystemet afhænger af tilgængelig teknologi og dermed af de teknologiske løsningers konkrete udformning, så vil det overordnet gælde, at lavkvalitets energi er lettere at fremskaffe end højkvalitets energi. Et eksempel er kraftvarmeverker, hvor det udover fremstillingen af elektricitet er nemt og dermed relativt billigt også at fremstille samproduceret varme til f.eks. fjernvarmedistribution.

Det samlede nettoenergiforbrug i figur 5.1 er ca. en tredjedel af 1992-niveauet. Tabel 5.3 giver tillige nogle tal for systemet anno 1992, men på grund af manglende statistiske data har det ikke været muligt at opdele tabellen så detaljeret som selve 2030-scenariet. Til gengæld er tallene for år 2030 omgrupperet, så de direkte kan sammenlignes med tabel 5.1 og 5.2. Det ses af opdelingen på energikvaliteter, at 2030 scenariet antager større effektivitet i køleanlæg (f.eks. køleskabe og fryser), i rumvarmeforsyning (bedre isolering og luftkontrol), og i procesvarmeforbruget (f.eks. lavtemperatur-varmeforbruget til opvarmning og varmtvandsforsyning af produktions- og salgslokaler, vaske-, opvaske og tørremaskiner samt industriel procesvarme i landbrug og industrivirksomheder).

Nogle af mulighederne er beskrevet i figur 5.2 og 5.3. Den danske fremstillingsindustri bruger idag ikke energien særligt effektivt, hvilket skyldes billig energi (både absolut og målt som procentdel af de samlede produktionsomkostninger) og manglende indsats for forbedringer som dem, der er sket på boligområdet.

Effektivitetsforøgelsen balancerer nogenlunde med den i scenariet antagne vækst i materiel produktion, idet Danmark ligesom den øvrige vestlige verden antages at udvikle sig fra et industriland til en mere vidensbaseret økonomi. Hvad angår den globale fordeling af opgaver er der to muligheder: Enten vil den egentlige produktion i fortsat stigende grad ske i nyindustrialiserede lande, eller vi vil basere en fortsat produktion på robotteknologi. Det sidste forudsætter, at denne teknologi bliver så billig og af så høj kvalitet, at den kan konkurrere med billig arbejdskraft i de nyindustrialiserede lande. For tiden ser det første alternativ ud til at være mest realistisk, og en omfattende

produktion i Danmark baseret på robotter kan have betydelige effekter på energiforbruget. Scenariet forudsætter en fortsat industriproduktion i Danmark som ikke ligger under det nuværende niveau.

Også elektriske apparater til telekommunikation, databehandling og underholdning ventes stærkt effektiviseret, fra dagens udgangspunkt med en meget stor spredning mellem gennemsnits- og mest energieffektive teknologier, der allerede idag er på markedet. Et eksempel er vist på figur 5.4. Det samlede forbrug af nødvendig elektricitet (altså hvor der ikke er iøjnefaldende substitutionsmuligheder med andre energiformer) antages imidlertid ikke at falde så kraftigt som effektiviseringen angiver, idet det antages, at mængden af elforbrugende udstyr vokser en hel del.

Det er også en forudsætning, at det mest energieffektive apparatur indføres hurtigt, hvilket er realistisk, fordi udskiftningsraten for de omhandlede apparater er høj. Men det forudsætter altså, at de ineffektive apparater tvinges bort fra markedet, enten ved konkrete godkendelsesprocedurer og/eller normer, eller som det er sket hidtil, ved at de mest effektive apparater havde andre fordele (spildvarme skader elektronik og giver hyppigere fejl!).

Endelig sker der i transportsektoren en betydelig effektivitetsforbedring gennem den teknologiske udvikling af tog, fly osv. Idag er effektivitetsstigningen gået i stå for skibe og biler, det første pga. det mindre behov for nye fartøjer i en kriseram sektor, det sidste fordi automobilindustrien under de seneste års faldende benzin og oliepriser har skrinlagt effektivitetsforbedrende ny-bil-projekter, der allerede findes. Det må pga. den individuelle transports globalt forekommende trafikale problemer såvel som forureningsproblemer (især i bymiljøer) forventes, at der sker en kraftig ændring af denne sektor over de næste 30 år, uanset behovet for større energieffektivitet.

Scenariet forudsætter et optimeret energiforbrug til transport af varer og pendling mellem hjem og arbejde, herunder at der ikke længere benyttes brændselsbaserede køretøjer i større byer, hvor en kombination af effektiv kollektiv trafik og eldrevne mini-bykøretøjer overtager billedet. Derudover er afsat et meget stort forbrug til sociale relationer, dvs. ferie- og fritidsrejser, besøg hos venner og familie i andre dele af landet, osv. Det samlede behov er med den antagne effektivitet af køretøjerne omkring 17 PJ pr. år. Transportarbejdet er omtrent det samme som i det lysegrønne scenarie, idet effektiviteten



af køretøjerne er ca. tre gange højere end i 1992, og brutto-brændselsforbruget iflg. tabel 5.3 ca. tre gange mindre.

Der er i scenariet taget hensyn til omlægningen af energisystemet til at blive baseret på vedvarende energi, idet der forudsættes opbygget en energisektor for omdannelse af biomasse til brændsler som biogas og flydende biobrændsler, og en udbygget industri til produktion af vindkraft- og solvarme/solcelle-anlæg. Denne industri erstatter den nuværende olie, gas og raffinaderi-aktivitet, og antages at tegne sig for et stort eksport-potentiale, som yderligere vil støttes af det danske energisystems omlægning. Tabellen i figur 5.1 angiver energiforbrugets opdeling mellem egentlig produktions-industri (omfattende produktion af energiudstyr) og en ressource og energiindustri, som omfatter driften af f.eks. biomasse-konverteringssystemerne og de dertil hørende egne energiforbrug.

Scenariets kraftige satsning på energieffektivitet er i første omgang en følge af den katastrofeagtige situation, som antages at have skabt konsensus om den hurtige udfasning af fossile brændsler. Imidlertid er det højst tænkeligt, at indsatsen for at højne effektiviteten i energiomsætninger overalt i systemet under alle omstændigheder vil være økonomisk attraktivt, hvilket vil sige billigere end enhver udvidelse af energiforsyningen. At det vil være sådan antydes af resultaterne vist i figur 5.7, der sammenfatter en lang række undersøgelser.<sup>6</sup>

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<sup>6</sup> Nørgård, 1989; Sørensen, 1982b, 1991

**Tabel 5.3 Nettoenergiforbrug opgjort efter traditionel metode.**

Enhed PJ pr. år	1992 *)	2030 lysegrønt scenarie	2030 mørkegrønt scenarie
Opvarmning	162	101	84
Apparater	44	41	21
Køling	15	13	7
Proces	132	134	62
Transport	174	160	64
Total	527	449	238

\*) Energistyrelsens tal

Noter til tabel 5.3:

Denne traditionelle måde at opgøre energibehov på er både inkonsistent og vildledende. Specielt i debatten om alternative udviklingsmønstre slører den traditionelle opgørelsesmetode muligheder og vilkår for at ændre udviklingen, ved at fokusere på indirekte og sammensatte størrelser, hvis direkte betydning er uklar, og hvor analyser derfor forføres til istedet at anvende eksponentielle fremskrivninger og andre traditionelle metoder. Disse udsagn kan illustreres ved at beskrive hvorledes det behovsopdelte nettoforbrug i figur 5.1 er oversat til de traditionelle kategorier i tabel 5.3:

"Opvarmning" består af rumvarme i boliger (43PJ), handels og servicebygninger (20PJ), offentlige institutioner (4PJ), samt varmt vand anvendt i boliger (15PJ) og service mm (2PJ), forudsat at det kommer ud af haner.

"Apparater" omfatter husholdningsapparater der bruger varmt vand (6.5PJ), som ikke er med ovenfor, opvarmning af mad på komfurer o.l. (1.5PJ), varme i tørretumblere mv. (1PJ), samt stationær mekanisk energi og elapparater i servicesektoren (4PJ). Endelig elforbrugende apparater som TV, lydforstærkere og hjemmecomputere i husholdningerne (8PJ).

"Køling" omfatter køle- og fryseaggregater i hjem og service såvel som industri, men ikke i transportmidler. Kategorien "køling" er ikke normalt opført i traditionelle

statistikker, men fandtes i en Risø undersøgelse af det danske forbrug af energi til køling.

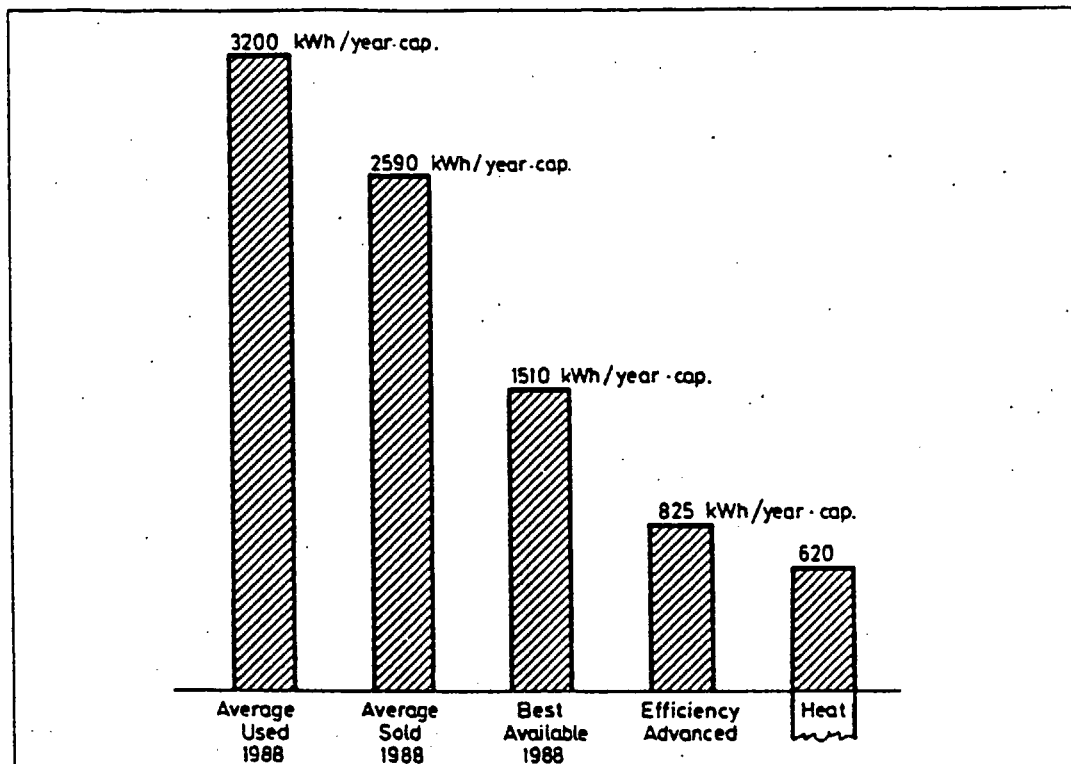
"Proces" dækker procesvarme i industri og landbrug (13PJ), men også rumopvarmning og varmt vand i disse sektorer (17PJ). Desuden omfattes stationær mekanisk energi i industri, bygge- og anlægssektoren såvel som landbrug (26PJ), samt industriens elforbrug (6 PJ), hvadenten det anvendes til proces eller til computere eller belysning.

"Transport" omfatter al transport, men er i modsætning til de øvrige størrelser opgjort brutto og ikke netto. Det mørkegrønne scenarios nettoenergiforbrug til transport (17PJ) kan derfor omsættes til 64 PJ energiskov.

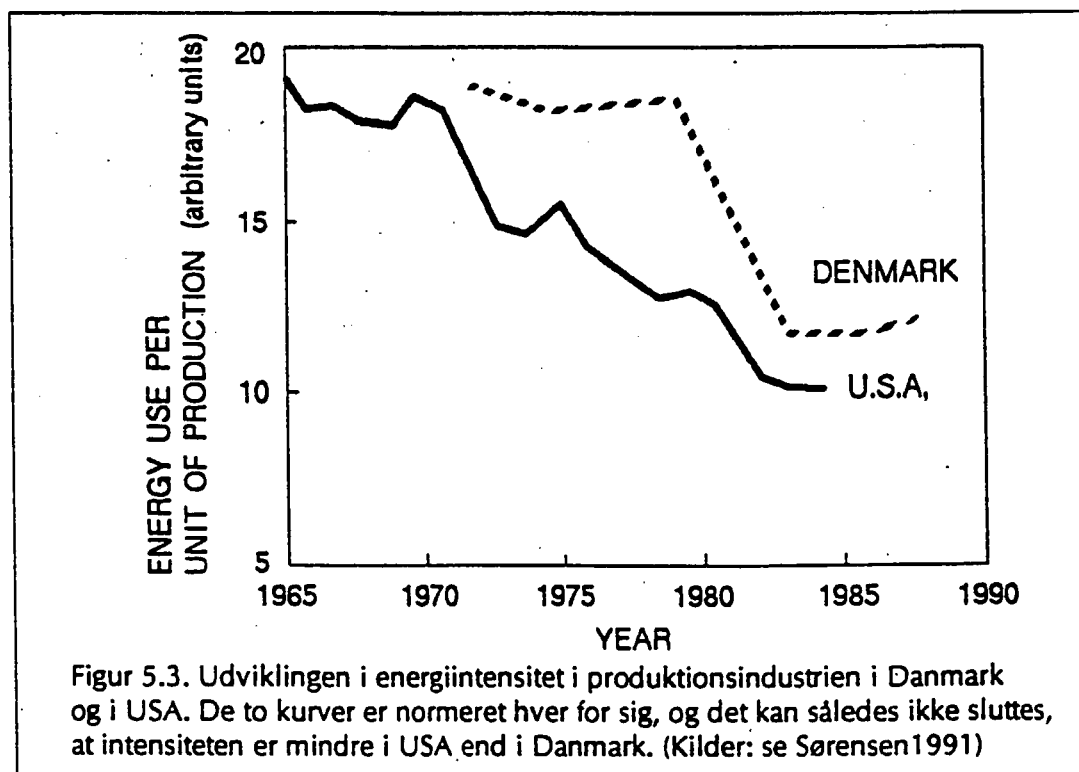
FIGUR 5.1. DANMARK 2030. MØRKEGRØNT ENERGISCENARIE: ET EFFEKTIVT OG MILJØBEVIDST SAMFUND  
 MED 5.3 MILLIONER INDBYGGERE: SLUTBRUGER-ENERGIBEHOV I PJ pr. år

	1. Køling	2. Rumopvarmning	3. Procesvarme under 100°C	4. Procesvarme 100-500°C	5. Procesvarme over 500°C	6. Stationær mekanisk energi	7. Elektriske apparater	8. Transport arbejde	9. Energi i fødevarer	TOTAL
A. Biologisk acceptable omgivelser	0	43	0	0	0	0	0	0	0	43
B. Mad og vand	3	0	0.5	1	0	0	0	0	20	24
C. Sikkerhed	0	0.2	0	0	0	0	0	0.1	0	0
D. Helbred	0	0	21.5	0	0	0	0	0	0	22
E. Samvær, fritid	0	0	0	0	0	0	8	6	0	14
F. Aktiviteter:										
Anlæg og bygning	0	0	0	0	0	10	0	1.5	0	12
Handel, service og distribution	2	20	2	0	0	1	4	4.5	0	33
Landbrug	0	0	2	0	0	1	0	0.5	0	4
Produktionsindustri	1.5	17	2	2	1	10	4	1.5	0	39
Råstof og energi-industri	0	0	2	2	2	5	2	1.5	0	14
Uddannelse	0	4	0	0	0	0	0.3	0	0	4
Pendling	0	0	0	0	0	0	0	1.5	0	2
TOTAL	7	84	30	5	3	27	18	17	20	211
skønnet 1992 niveau	5	70	18	4	3	25	10	26	20	

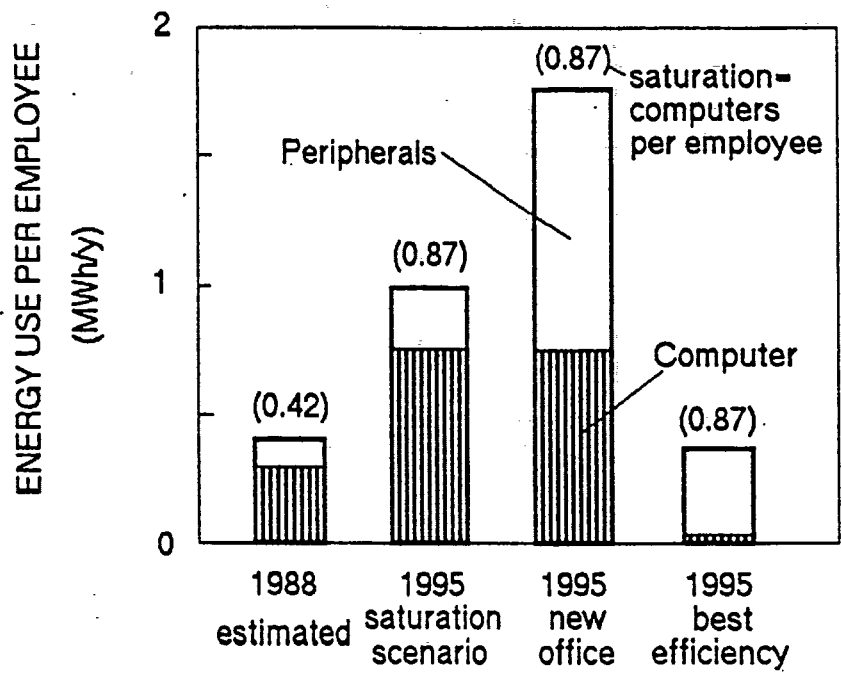
[INDEHOLDER SKØN OG USIKRE TAL]



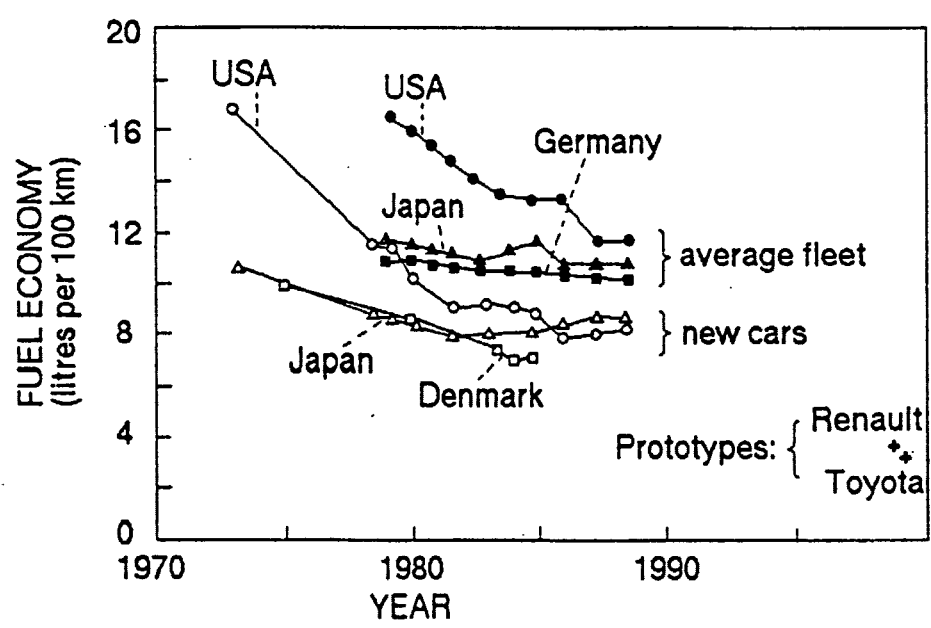
Figur 5.2. Elforbrug for apparater og belysning i husholdninger, service og handel i Danmark, samt vurdering af elforbruget for den bedste teknologi på markedet, og for teknologi under udvikling (Nørgård, 1989).



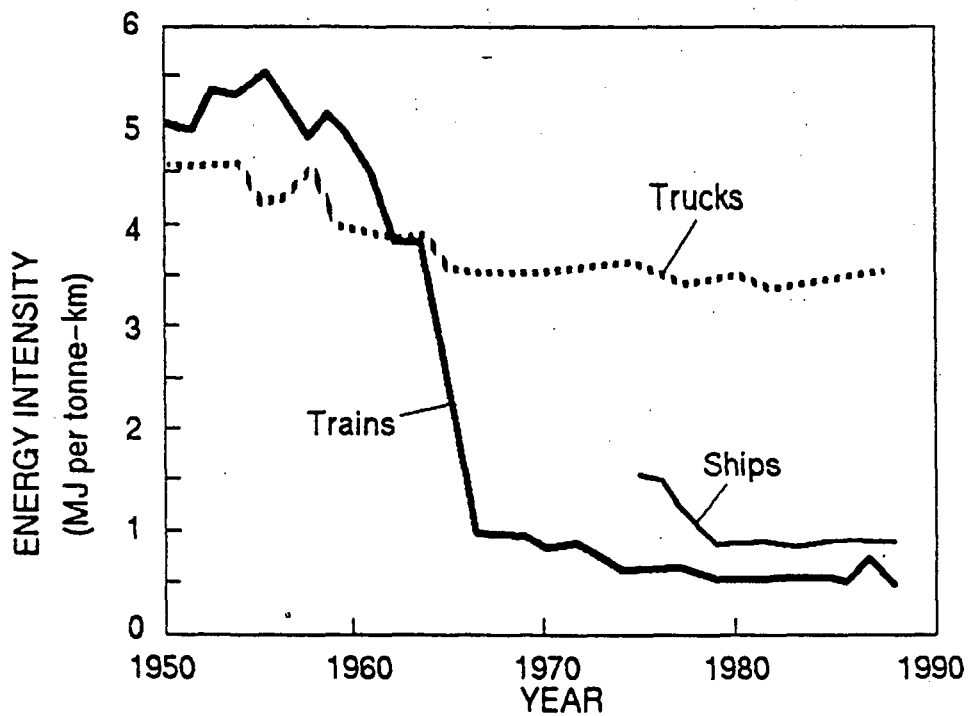
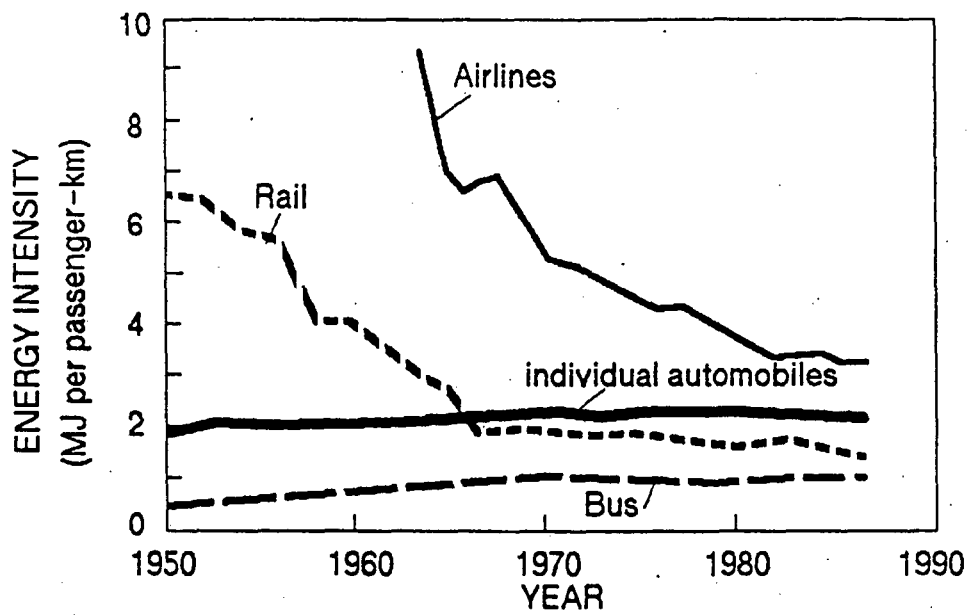
Figur 5.3. Udviklingen i energiintensitet i produktionsindustrien i Danmark og i USA. De to kurver er normeret hver for sig, og det kan således ikke sluttes, at intensiteten er mindre i USA end i Danmark. (Kilder: se Sørensen 1991)



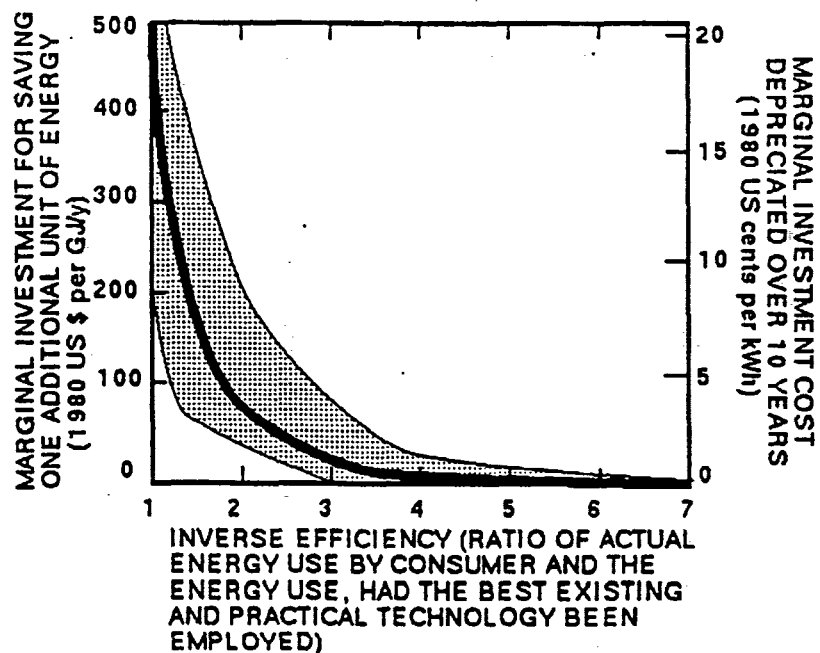
Figur 5.4. Elforbrug for computersystemer i kontormiljøer. Tallene for 1988 og prognosen for 1995 refererer til USA, hvor der er indregnet en 25% stigning i antallet af kontomedarbejdere fra 1988 til 1995. Mætning betyder 87 computere pr. 100 medarbejdere, "new office" inkluderer scannere og en række sort-hvid og farveprintere. "Best efficiency" refererer til det mest energieffektive udstyr på markedet i 1991 (Norford et al., 1989, Sørensen, 1992).



Figur 5.5. Energi-intensitet af personbiler i udvalgte lande (baseret på en række kilder, se Sørensen, 1991).



Figur 5-6. Udviklingen i energiintensitet af passager (foroven) og fragt (forneden) transport i UK, specificeret på forskellige transportmidler. (baseret på flere kilder, se Sørensen, 1992).



Figur 5-7. Marginal-omkostningerne ved at øge effektiviteten af slutenergi-leverancer, som funktion af hvor meget der tidligere er gjort. Skalaen til venstre giver totalinvesteringen for at spare den næste enhed af energi, mens skalaen til højre giver den årlige afskrivning ved 4% realrente. Det skraverede areal antyder spredningen mellem forskellige teknologier, på industri, transport, og apparatområdet (fra Sørensen, 1982b, 1991).



## Kapitel 6. Energiforsyning

### 6.1 Energiforsyningen i dag

Det samlede bruttoenergiforbrug i Danmark i 1992 er angivet i tabel 6.1.

*Tabel 6.1 Bruttoenergiforbrug i 1992.*

1992	Bruttoenergiforbrug	
	PJ	pct.
Olie	331	43
Kul	286	37
Naturgas	91	12
Biomasse	51	6
Sol-varme	-	-
Sol-el	3	-
Vind-el	14	2
Import-el		
Ialt	776	100

Kilde: Energistyrelsen.

Godt halvdelen af olieforbruget udnyttes i transportsektoren, og ca. 90 pct. af kulforbruget ligger i el- og kraftvarmesektoren. Af det samlede bruttoenergiforbrug (incl. import og vind) går ca. 300 PJ eller knap 40 pct. til el- og kraftvarmeproduktion.

### 6.2 Et lysegrønt scenarie for energiforsyningen år 2030

#### El-forsyning med stor andel vedvarende energi

Det primære tekniske problem i en dansk energiforsyningsstrategi, der stiler mod en meget høj VE-dækning, er at sikre en stabil elforsyning. En betydelig del af elproduktionen i et kraftigt VE-baseret elforsyningssystem i Danmark vil være fluktuerende

elproduktion fra vindkraftanlæg m.v., og dette stiller store krav til resten af elsystemet. Resten af systemet skal sikre at elproduktion og -efterspørgsel til stadighed er i balance, samt at den ønskede kvalitet i elforsyningen opnås.

Man kan tænke sig flere muligheder for at tilvejebringe effektbalance mellem produktion og forbrug af elektricitet. Den fornødne reguleringsevne kan tilføres på elsystemets forsyningside, men også på forbrugssiden kan der opnås en tilpasning, hvor dele af elforbruget kan flyttes til tidspunkter, hvor f.eks. produktionen af vindkraft er høj. F.eks. kunne man tænke sig eldrevne biler, der oplades når der er eloverskud eller vaskemaskiner der går i gang, når der er eloverskud.

Elproduktionskapacitet med høj reguleringsevne øger systemets muligheder for at absorbere en fluktuerende elproduktion. Elforsyningskapacitet med reguleringsevne, som den kendes i dag, vil i fremtidens vedvarende energisystem være en efterspurgt vare, og tilførsel af den nødvendige reguleringsevne og kapacitet kan være meget bekostelig. Af danske VE-ressourcer er det i det væsentlige kun de begrænsede mængder biomasse, der giver direkte basis for elproduktion med reguleringsevne. Biomassen kan lagres og kan derfor forbruges på de ønskede tidspunkter.

På elforsyningsiden kan der nævnes følgende muligheder for at øge systemets evne til at følge efterspørgslen:

1. Høj reguleringsevne samt høj el- og varmevirkningsgrad og brændselsfleksibilitet kan tilstræbes ved valg af elproduktionsteknologi, der udnytter fossilt brændsel, biomasse eller VE-baserede sekundære brændsler.
2. Øget international handel med:
  - Elektricitet.  
Kraftige eltransmissionsnet, som forbinder store geografiske områder, giver mulighed for at drage fordel af øget statistisk udjævning på både forbrugs- og produktionssiden af elsystemet. Reguleringsevne i det større system f.eks. fra vandkraft vil endvidere kunne udnyttes bedre.
  - Andre VE-baserede energibærere, der kan lagres og indgå i elforsyningen.

3. El-lagre kan inddrages i systemet, f.eks. i form af batterier, pumpekraftværker m.v. og på længere sigt også brintteknologi (reversible brændselsceller).

På elforbrugssiden kan som nævnt en øget tilpasning til produktionssiden opnås ved at flytte dele af elforbruget til andre tidspunkter ("load management"). Uden væsentlig reduktion i energitjenestens værdi kan elforbrug forskydes til tidspunkter, der er tilpasset elproduktionen.

I fremtidens vedvarende energisystem vil man formentlig se alle sådanne muligheder udnyttet hen imod en optimeret balance mellem mulighederne på systemets forsynings- og forbrugsside.

### **Primære teknologier i fremtidens vedvarende energisystem**

Her omtales alene de teknologier, der anses for centrale på længere sigt i opbygningen af et el- og varmforsyningssystem med udbredt anvendelse af vedvarende energi. Foruden disse primære teknologier vil en mangfoldighed af andre teknologier kunne forventes at finde indpas i fremtidens vedvarende energisystem.

Kernekraft i form af fission lades ude af betragtning, og fusionsenergi forudsættes også på lang sigt ikke at være til rådighed for energiforsyningen.

### **VE-baseret elproduktion uden reguleringsevne**

#### **Vindmøller:**

Vindkraft er som bekendt anvendt teknologi i elforsyningen i dag, og gode mølleplaceringer giver i dag god økonomi.

Det teknologiske udviklingspotentiale på vindkraftområdet er fortsat stort. Forskning og udvikling kan forventes fremover at forbedre bl.a. rotorvirkningsgraden og dermed elproduktionen fra vindmøller betydeligt. Dette samt fortsat udvikling af mølledesign, optimering af produktionsgang m.v. forventes at medføre væsentlige prisreduktioner for elektricitet fra vindkraftanlæg fremover.

### **Solceller:**

Elproduktionen fra solceller placeret i Danmark er naturligvis knap så gunstig som fra celler placeret i mere solrige områder ved lavere breddegrader. En meget betydelig udviklingsindsats pågår internationalt, og i de senere år har markedet for solceller været kraftigt ekspanderende, men endnu er økonomien ikke attraktiv for storskala elproduktion. Forventningerne til den teknologiske udvikling på solcelleområdet er store også på kort sigt, og solcellerne kan meget vel blive attraktive for elforsyningen på noget længere sigt også i Danmark.

I elsystemet er elproduktion fra solceller i dagtimerne gunstig i fase med spidslasttidspunkterne, men produktionen er lav i vintermånederne, hvor til gengæld vindressourcerne er gode. I arealudnyttelse er solceller energiafgrøder langt overlegne når formålet alene er elproduktion. Solceller integreret i tagflader er dog den forventede placering. Med denne placering er energipotentialet fra solceller i Danmark af samme størrelsesorden som elbehovet.

### **Bølgekraft:**

Bølgekraft fra danske farvande kan have meget høj energiintensitet, men i dag synes ressourcen svær at udnytte med acceptabel økonomi. Energipotentialet fra denne ressource er betydeligt mindre end for de førnævnte ressourcer, men potentialet er ikke uvæsentligt.

### **VE-baseret elproduktion med reguleringsevne**

Biomasse er i det væsentlige den eneste vedvarende energiressource i Danmark, der giver direkte grundlag for elproduktion med reguleringsevne. I et dansk elforsyningssystem, der sigter mod indpasning af vedvarende energi i betydeligt omfang, er det derfor væsentligt at biomassen udnyttes i anlæg med høj virkningsgrad og reguleringsevne på elsidens.

Høj elvirkningsgrad og reguleringsevne har man i dag bl.a. på gasbaserede combined cycle-anlæg (gasturbine efterfulgt af damp-turbine), og på længere sigt forventes brændselsceller udviklet, der i høj grad kan opfylde sådanne krav. Fælles for de nævnte

teknologier er, at brændslet er på gasform. Forgasning af de knappe biomasseressourcer er bl.a. af denne grund interessant.

Forgasning af biomasse må i lighed med kulforgasning om få år kunne betegnes som kendt teknologi. For visse typer biomasse udgør indfødning, korrosion i reaktorer og gasrensning endnu problemområder, der dog forventes at kunne løses på kortere sigt ved en målrettet udviklingsindsats.

Fastoxid-brændselscellen (Solid Oxide Fuel Cell, SOFC) er særlig interessant i relation til fremtidens vedvarende elforsyningssystem. SOFC-brændselscellen er en såkaldt reversibel højtemperatur brændselscelle, der er meget fleksibel over for den kemiske sammensætning af gasserne på brændselssiden. SOFC-teknologien må siges endnu at være på laboratorieniveau, og kun prototypeanlæg i mindre skala er bygget. Der er imidlertid udbredte forventninger til, at anlæg i stor skala kan være til rådighed for elforsyningen på omkring 15 års sigt.

Reversible brændselsceller kan tilføre elsystemet meget betydelig reguleringsevne. Sådanne celler vil kunne regulere elproduktionen ned til "negativ elproduktion" i lighed med opladelige batterier. Overproduktion af elektricitet f.eks. fra vindkraftanlæg i systemet kan forbruges i de reversible brændselsceller, der i den reverserede driftsform producerer brint og ilt ved vandsønderdeling (elektrolyse). Gasserne brint og ilt kan lagres for sidenhen at blive anvendt f.eks. henholdsvis i brændselsceller til el- og varmeproduktion og i forgasningsprocesser. En anden mulighed for at udnytte eloverløb er at have varmepumper installeret i tilknytning til kraftvarmeområder.

Det danske naturgasnet fordeler store energimængder til alle større byområder i landet og danner endvidere forbindelse til udlandet. Den udbredte teknologiske viden på naturgasområdet kan også udnyttes ved håndtering af andre gasser, der måtte indgå i fremtidige VE-baserede energisystemer. Lagring af gas er velkendt teknologi, og der er i Danmark meget gunstige muligheder for at lagre store gasmængder billigt i undergrunden f.eks. i kaverner udskyllet i salthorste, i aquiferer eller på sigt i tømte naturgasfelter.

### **Karakterisering af forsyningsiden i fremtidens vedvarende energisystem**

De væsentligste karakteristika på forsyningsiden er:

- På grund af det faldende varmebehov er fjernvarmeområder konverterede til lavtemperatursystemer.
- Fjernvarmeområder er praktisk taget totalt forsynet med kraftvarme. Kraftvarmeværkerne er baseret på bioforgasning (ca. 2 GW) og naturgasfyrede brændselsceller (ca. 4 GW). En del af brændselscellerne kan med fordel være reversible. Herudover er der ca. 1.5 GW decentrale kraftvarmeværker, hovedsagelig baseret på biomasse.
- Kondensproduktion (elproduktion uden varmeudnyttelse) er reduceret til et minimum, og varmelagre anvendes på kraftvarmeværkerne til udjævning af varmebelastningen, og dermed opnås bedre reguleringsevne for elproduktionen.
- Store kapaciteter vindkraft (ca. 3.5 GW) og solceller (ca. 1 GW) er installeret. Der må forventes et moderat eloverløb fra disse teknologier, til trods for at bl.a. reversible brændselsceller anvendes til at opsuge overskuddet.
- Biomasse, vind og sol dækker knap 1/3 af det samlede bruttoenergiforbrug. I elsystemet er restforbruget hovedsageligt naturgas. Ca. 2/3 af el- og kraftvarmeproduktionen er baseret på vedvarende energi.

Det samlede bruttoenergiforbrug er angivet i tabel 6.2.

#### **Kort karakterisering af forsyningsscenariet**

Kendetegnende for det beskrevne forsyningsscenarie er, at brændselskonverteringen i el- og varmforsyningen i stort omfang involverer gasteknologi. Naturgas er det dominerende fossile brændsel i elforsyningen, og biomasse forudsættes i dette system opgraderet som brændsel via forgasning.

Endvidere er systemet karakteriseret ved, at en meget stor del af el- og varmeproduktionen udnytter elektrokemiske processer (brændselsceller). Termiske processer, som i dag dominerer elproduktionen, udnyttes i fremtidens vedvarende energisystem hovedsagelig i anlæg, der danner "bottom cycle" for brændselsceller, dvs. i anlæg, der udnytter varme og restgasser fra brændselsceller til yderligere elproduktion.

Systemet er i hovedtræk et integreret forsyningssystem, der udnytter de store kollektive net til fordeling af el, varme og gasser, og som kan udnytte de statistiske og skaleringsmæssige fordele der følger heraf.

**Tabel 6.2 Bruttoenergiforbrug i 1992 samt i det lysegrønne scenarie.**

	Bruttoenergiforbrug			
	1992		2030	
	PJ	pct.	PJ	pct.
Olie	331	43	246	43
Kul	286	37	22	4
Naturgas	91	12	146	25
Biomasse	51	6	119	21
Sol-varme	-	-	4	1
Sol-el	-	-	4	1
Vind-el	3	-	32	5
Import-el	14	2	-	-
<b>Ialt</b>	<b>776</b>	<b>100</b>	<b>573</b>	<b>100</b>

År 2030 udnytter el- og kraftvarmesektoren ca. 230 PJ eller 40 pct. af det samlede bruttoenergiforbrug (incl. import m.m.), og godt 60 pct. af scenariets olieforbrug udnyttes i transportsektoren.

Den samlede emission af CO<sub>2</sub> udgør i år 2030 ca. 24 mill. tons mod ca. 56 mill. tons i 1992.

#### **Integrationsmuligheder med transportsektoren**

Batteribaserede eller tilsvarende eldrevne køretøjer kan give gunstige muligheder for at flytte elforbrug til tidspunkter, hvor det passer bedre med elproduktionen i elsystemet.

Produktion af brint på reversible brændselsceller som drivmiddel til transportsektoren er en mulighed i dette forsyningssystem. Endvidere kan produktion af metanol som

drivmiddel til transportsektoren via biomasseforgasning integreres i det skitserede energisystem.

### **6.3 Et mørkegrønt scenarie for det danske energisystem år 2030**

I dette afsnit opstilles et energiforsynings-scenarie svarende til forbrugs-scenariet opstillet i kapitel 5.3. Det er en forudsætning for scenariet, at fossile brændsler er helt udfaset inden scenarieåret 2030. Der er ikke regnet på omkostninger forbundet med overgangen til dette scenarie, idet det forudsættes, at livscykluspriser har vundet accept indenfor energiområdet, og idet det netop er en forudsætning for det opstillede scenarie, at livscyklusudgifterne til energiforsyning baseret på fossile eller nukleare energikilder er vurderet som for høje (jvf. diskussionen i kapitel 7). Først gives en oversigt over de tilgængelige vedvarende energikilder.

#### **Vind**

Idag leverer vindkraftværker ca. 3 PJ om året i form af elektricitet. Der skønnes at være opstillet 3.000-4.000 møller i Danmark, med en samlet mærkeeffekt på over 400 MW. Den gennemsnitlige energiproduktion svarer til 100 MW. De første møller i den moderne udbygningsfase blev opstillet sidst i 1970'erne. Den enkelte mølles mærkeeffekt var i starten 15-30 kW, og de følgende år steg den (økonomisk) optimale mærkeeffekt systematisk. Idag er den 400-500 kW pr. mølle, og ventes i de nærmeste år at overstige 1 MW.

Det forudsættes i scenariet, at forøgelsen i møllestørrelse vil fortsætte, omend i dæmpet tempo, således at den gennemsnitlige mærkeeffekt pr. mølle i år 2030 er mindst 2 MW. Samtidig vil den enkelte mølles effektivitet stige lidt, således at den faktiske produktion bliver 30 pct. af mærkeeffekten istedet for dagens 25 pct. for 400 kW møller. Dette er en behersket antagelse, idet møllerne bliver højere og derfor møder bedre vindforhold, således at der kun skal en minimal teknisk forbedring til at nå de 30 pct. (som forøvrigt allerede er nået af flere møller i udlandet).

Scenariet forudsætter at mølleantallet holdes på 4.500, men at de nuværende udskiftes med de større 2 MW møller, så der leveres 90 PJ årligt. Herved sikres, at de bedste placeringer bevares for vindkraft, omend der kan blive tale om at flytte en større procentdel af møllerne til vindpark-lokaliteter eller off-shore, når lokale (visuelle) miljøfor-



hold taler imod udskiftningen til større møller på samme sted. Under alle omstændigheder forekommer antagelsen om 4.500 møller at udgøre en behersket forventning, og dette antal kan tænkes forøget, hvis behovet for energi skulle stige udover det i scenariet forudsatte.

## Sol

Solvarmeanlæg leverer idag ca. 0.2 PJ pr. år. Anlæggene er baseret på flade absorbere med selektiv overflade og en effektivitet på ca. 50 pct. Det vil sige at der leveres ca. 1.6 GJ pr. år pr. kvadratmeter solfanger. Da solfangerens effektivitet afhænger af det gennemstrømmende vands temperatur, gælder dette kun for den kombination af solfangerstørrelse og størrelse af varmtvandslager, som er typisk idag (3-6 kvadratmeter solfangerareal, 200-400 liter vandlager). Større anlæg vil have lavere effektivitet, med mindre lagerforholdene kan udbygges tilsvarende, hvilket ikke ses som rentabelt idag.

Tænkes i første omgang på solfangere monteret på tage og bygningsfacader, er udgangspunktet det idag bebyggede areal, som i Danmark er 420 millioner kvadratmeter. Tages der hensyn til orientering og skyggeforhold, findes et egnet areal i størrelsesordenen 200 mio. kvadratmeter.

For at kunne levere de i scenariet forudsatte 40 PJ pr. år af solvarme, ville med samme effektivitet som dagens systemer kræves et areal på 25 mio. kvadratmeter eller ca. 6 pct. af det bebyggede areal. Imidlertid ventes som nævnt de større anlæg at have lavere effektivitet, så der må i praksis regnes med et areal på mindst det dobbelte. Lige omkring det dobbelte synes at gælde hvis dagens solfangere baseret på evakuerede rør blev anvendt. Hovedparten af energien leveres i sommerhalvåret, og der forudsættes derfor kombination med fjernvarme eller anden varme, der kan leveres "i modfase", således at forbrugsmønstrrets variation over året følges.

Solceller til produktion af elektricitet har idag en effektivitet på 8-10 pct. (amorfe celler anno 1994) til 15-21 pct. (krystallinske celler). Potentialet for billiggørelse synes størst for amorfe celler, omend tyndfilms krystallinske eller polykrystallinske celler kan komme på tale. Der er derfor regnet med, at effektiviteten af de i 2030 anvendte celler er 15 pct., hvilket under danske forhold giver en produktion på 0.5 PJ pr. år for hver million kvadratmeter solceller.

Scenariet forudsætter 25 PJ solcelle-elektricitet pr. år, svarende til 50 millioner kvadratmeter rimeligt orienterede tagflader eller bygningsfacader. Dette svarer til ca. 12 pct. af det bebyggede areal, således at det samlede areal dedikeret til solvarme og solceller bliver af størrelsesordenen 20-25 pct. af det bebyggede areal og en lignende procentdel af sydligt orienterede bygningsflader.

Der findes idag omkring 4.000 varmepumpeanlæg, der dækker ca. 0.4 PJ pr. år ved varme fra omgivelserne, og brug af typisk 1 enhed elektrisk energi for hver 4-6 enheder af varme bjærg. Varmepumper indgår i betydelig grad i det mørkegrønne scenarie, dels til løft af temperaturen af solvarme og staldvarme, dels baseret på varme fra omgivelserne (jord, vand - evt. kølevand fra kraftværker - eller luft). I figur 6.4 er varmepumperne kun angivet som centralt placerede, f.eks. i forbindelse med fjernvarmeværker, men i praksis vil en betydelig del af dem findes i forbindelse med enkelte bygninger.

### **Biomasse**

Vurderingen af, hvor meget energi der kan leveres fra biomassesektoren (landbrug, skovbrug, fiskeri og havbrug) kræver en samlet model for fødevarereproduktion, energi og materialer som træ og andre vegetabiliske og animalske non-food råvarer. En sådan model er forsøgt opstillet i figur 6.3, svarende til modellen i figur 6.1 opdelt tilsvarende for det nuværende landbrugssystem. Det er ikke forsøgt at modellere fiskeri og havbrug, som derfor ikke indgår i det opstillede scenarie, men kan tænkes at levere yderligere input til de nævnte anvendelser.

Udover officielle statistikker har det været nødvendigt at tilføje en række skøn og selvstændige beregninger. Kilderne hertil omfatter Ansbæk et al. (1973), Illum et al. (1984), Jensen og Sørensen (1984), og ved projektafslutningen Teknologinævnet (1994). Udviklingen for afsætning af landbrugets produkter er inde i en overgangsfase, hvor omlægning til nye produkter eller økologiske versioner af gamle produkter spiller en væsentlig rolle, ligesom EU's landbrugspolitik og udviklingen i priser og konkurrenceforhold er en del af denne problematik. Opsummerende kan det siges, at den danske landbrugssektors overlevelse er tæt forbundet med overvejelserne om en overgang til en kombineret landbrugs-, skovbrugs- og bioenergi-produktion, og at branchen er fuldt bevidst om nogle af de muligheder, som denne omlægning indebærer (cf. Teknologinævnets ovenfor nævnte biomasseprojekt, Teknologinævnet (1994)).

Scenariet opstillet i figur 6.3 omfatter en ca. 30 pct. nedgang i areal dyrket med fødevarer-høst som formål (til dels med braklægningsstøtte!). Det frigjorte areal udnyttes til specielle energiafgrøder og energiskov, samtidig med at energiudnyttelsen af den fødevarerrelaterede høst optimeres. På et seminar i forbindelse med Teknologinævnets biomasseprojekt blev der stillet spørgsmål ved, om landmanden ville gøre en ordentlig indsats for energihøsten, når det nu ikke var hans/hendes primære branche. Det er det foreliggende scenarieres antagelse, at landbrugssektoren meget vel kan omfatte energi i sit produktsortiment med optimal håndtering, ligesom sektoren har været vant til at skulle støtte såvel vegetabilsk og animalsk produktion, uden at nogen vist vil påstå, at det er gået ud over nogen af delene.

Scenariet i figur 6.3 forudsætter samme dyrkede areal som i 1992. Imidlertid kan energiindholdet i de afgrøder og træer, som dyrkes alene med energiformål for øje, være anderledes end i den traditionelle landbrugsproduktion, hvilket vil medføre en fordeling af arealer, der ikke er proportional med den høstede energi. Typisk kan man forestille sig, at energiudbyttet for rene energiafgrøder er større end for primær fødevarerproduktion (dvs. mindre arealkrav), mens den for energiskov typisk vil være mindre, da den forudsættes baseret på træ. Valget mellem træ (ligninholdig biomasse) og andre bioafgrøder er dikteret af den valgte teknologi for den videre omdannelse, hvor det idag ser ud til, at træ-til-methanol vejen er både økonomisk og energimæssigt fordelagtig, relativt til fermenterings-løsninger (f.eks. korn-til-ethanol)

Der er fokuseret på to energiprodukter, hvor det ene er flydende biobrændsel (f.eks. methanol) til transportsektoren. Dette etableres bedst gennem forgasning af træ fulgt af methanolsyntese.<sup>7</sup> F.eks. kan anvendes poppel. Da den estimerede omdannelses-effektivitet er ca. 45 pct., skal der altså høstes energiskov svarende til 47 PJ om året, for at producere scenariets 22 PJ flydende biobrændsel. Potentialet er væsentligt større, så der er mulighed for også at dække forbruget af flydende brændsler i mere energikrævende scenarier, eller at anvende brændslet som lager og back-up for de vedvarende energikilder i systemet. Dette kan vise sig vigtigt ved en detaljeret undersøgelse af flaskehalse i en tidlig simulering af scenariets energisystem.

Det andet hovedprodukt er biogas, som kan produceres ud fra en blanding af halm, gylle, organisk affald og særlige energiafgrøder (typisk etårige vækster med højt energiindhold). Den skønnede effektivitet i omdannelsen til biogas er optimalt 50-60 pct.<sup>8</sup>, hvilket står i rimeligt forhold de tidlige erfaringer med de større biogas-pro-

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<sup>7</sup> Jvf. Jensen og Sørensen, 1984

<sup>8</sup> Jensen og Sørensen, 1984

duktionsanlæg, som fungerer idag (total produktion 1.5 PJ pr. år). Også i dette tilfælde er de i scenariet anvendte 45 PJ væsentligt lavere end potentialet. Som biomasse anvendes bio-affald og restprodukter fra dyrkningen (f.eks. halm, der ikke forudsættes brændt).

Der er andre energimuligheder i landbruget, f.eks. i forbindelse med det overskud af varme, som besætninger producerer i stald over en betydelig del af året (særlige forhold gør sig gældende i perioder med mange spæde kalve og grise), og som idag ikke udnyttes, fordi isoleringsgraden af staldbygninger ofte er lav. Det er i scenariet antaget, at isoleringsgraden øges, og at ca. 6 pct. af varmeproduktionen anvendes til opvarmning af stuehuse o.a. bygninger, der måtte befinde sig i nærheden af staldene. Varmens temperatur kan evt. løftes af varmepumper, og i enkelte tilfælde vil der være muligheder for at indføre varmeoverskud til fjernvarmenet. Dette giver store fordele i forbindelse med de solbaserede opvarmningssystemer, idet årstidsvariationerne er modsat (der anvendes naturligvis kun staldvarme om vinteren, når svin og kreaturer er i stald). I figur 6.4 er staldvarmen for overskuelighedens skyld blot angivet som gående til forbrugerne af rumvarme.

Modellen af landbrugssektoren er stadig preliminær og skal kun tjene til at sandsynliggøre, at de påståede mængder af primært biogas og flydende brændsler er opnåelige indenfor en ikke altfor stresset omlægning af det nuværende landbrug, en omlægning der indebærer yderligere fordele og i sidste ende kan være nødvendig for sektorens overlevelse.

### **Samlet scenarie for energisektoren 2030**

Figur 6.4 opsummerer energistrømmene i det samlede danske energisystem, svarende til det her opstillede scenarie. Et forsøg på at beskrive det nuværende energisystem på samme detaljeringsniveau, med de indskrænkninger, som er nævnt i afsnit 5.3, kan findes i figur 6.2.

Et særligt problem ved overgangen til et energisystem baseret på vedvarende energi er udnyttelsen af den infrastruktur, som allerede er opbygget. Dette gælder ikke mindst fjernvarmenet, gasnet og naturligvis elektricitetsnettet. Det sidste er der næppe problemer med at udnytte, inklusiv de kraftige udlandsforbindelser, som i det foreliggende scenarie tjener til lastudjævning.

Hvad angår naturgasnettet, vil det i vid udstrækning kunne fortsætte med at gøre nytte ved distributionen af biogas, som antages anvendt såvel i industrivirksomheder som ved individuel opvarmning af bygninger.

Også fjernvarmenettet er i stadig brug, i forbindelse med levering af fjernvarme produceret på et (reduceret) antal kraftvarmeværker, samt på et antal brændselscelle-kraftværker, der antages at producere elektricitet med en virkningsgrad på 50-60 pct. og altså varme for restens vedkommende. Brændselscellerne er antaget reversible, og der regnes med høj effektivitet i elektricitet-til-brændsel omdannelsen. Nogle brændselsceller kan befinde sig decentralt, for eksempel i større bygninger.

Fjernvarmetilslutningen spiller en vigtig rolle i forbindelse med det betydelige solvarmebidrag, som jo forekommer "skævt" i forhold til rumvarmeforbrugets variation gennem året. Der er derfor tilføjet lagre til biogas (f.eks. i salthorste), og en vis del af vindkraft og solcellekraft produktionen ledes gennem de reversible brændselsceller til oplagring som brændsler. Dette supplerer anvendelsen af staldvarme i at følge varmeforbrugets variationer gennem året, og det lille antal kraftvarmeværkers produktion styres primært af varmeforbruget.

Dette betyder, at tilpasningen til variationer i elforbruget skal styres på anden vis. Her er der ikke forudsat lagring med ny elproduktion for øje, udover de nævnte gaslagre samt et stærkt øget antal batteriopladere hos slutbrugerne, som bruges i forbindelse med bekvemmeligheden af bær- og flytbare elforbrugende apparater, men som også tillader en hensigtsmæssig tilpasning af ihvertfald dag-til-nat variationer i elforbrug og -produktion. Imidlertid er der klart et rest-behov for effektudjævning, både indenfor døgnet og med længere forskydning, forårsaget af variationer i sol- og vindkraft tilgang, på ugebasis (passage af frontsystemer) og på årstidsbasis.

Udglatningen af disse variationer tænkes at ske ved hjælp af udlandsforbindelser. Dels er der altid mulighed for effektudjævning i et stort system med forskellige forbrugsmønstre og produktionsformer, dels er som bekendt en meget stor del af Nordeuropas elektricitetsproduktion baseret på vandkraftanlæg med reservoirer der gennemløber en årscyklus. Studier af sammenhængen mellem vandkraftproduktion i f.eks. Norge og vindkraftproduktion i Danmark har vist, at samkøring af disse systemer er til gensidig fordel. For Danmark af de ovenfor nævnte grunde. For Norge fordi maksimum vindproduktion i Danmark forekommer når vandstanden i de norske reservoirer er lavest,

og fordi der ikke er sammenhænge der sammenkobler dårlige vandår med dårlige vindår.<sup>9</sup>

Tabene i brændselsbaserede konverteringsanlæg og distributionssystemer antages at være som de bedste anlæg i dag. Specielt for fjernvarmeledningerne nedsættes tabene, fordi temperaturen skal sænkes for at anlæggene kan køres i kombination med solvarme. Dette kræver ikke yderligere udbygning, idet der løber tilsvarende mindre varmemængder gennem ledningerne, som følge af bedre isolering mv. hos slutbrugerne.

Procesvarme ved høje temperaturer udnyttes i et fåtal industrier, og det antages at varmen kan udnyttes igen ved lavere temperatur (kaskade-system), enten indenfor den samme eller en nærliggende industri der anvender mellemtemperaturer. Også fra mellem-til lav-temperaturer er der antaget en kaskade-udnyttelse, men her ved udledning i fjernvarmenettet. Kun ca. en tredjedel af spildvarmen antages at kunne udnyttes.

Transportsektoren antages at ændre sig i betydelig grad fra 1994 til år 2030. Bymiljøerne antages kun at tillade eldrevne køretøjer, og der antages udviklet en særlig type bybil med høj effektivitet (og plads til 1-2 personer pr. køretøj). Hjem-arbejde pendling sker (f.eks. arrangeret af arbejdsgiver) ved hjælp af minibusser, der ligesom varetransporten optimeres gennem brug af informationssystemer. Den kollektive togtrafik udbygges og elektrificeres totalt. Alt i alt varetages ca. halvdelen af transportarbejdet af eldrevne køretøjer, og den anden halvdel af brændselsbaserede køretøjer (inkl. fly og skibe).

I tilfælde af, at en detaljeret tids-simulering udviser lagringsbehov, som ikke kan klares ved import/eksport (som i et tilfælde) eller ved øget brug af flydende biobrændsler (som kan oplagres billigt), så er det altid muligt, og af forsyningsmæssige grunde formentlig hensigtsmæssigt, at bibeholde et antal (evt. af de eksisterende) konventionelle brændselsbaserede konverteringsanlæg til håndtering af særligt vanskelige resource-til-forbrug tilpasningssituationer. Brændselsforbruget til sådanne reserveanlæg vil formentlig blive minimalt set over længere perioder.

Tabel 6.3 opgør bruttoenergitilførslen i scenariet på en måde, som er direkte sammenlignelig med det lysegrønne scenarie og nutidens bruttoenergiforbrug.

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<sup>9</sup> Sørensen, 1981b

**Tabel 6.3 Bruttoenergitilførsler.**

Enhed PJ pr. år	1992 *)	2030 lysegrønt scenarie	2030 mørkegrønt scenarie
Olie	331	246	0
Kul	286	22	0
Naturgas	91	146	0
Biomasse	49	119	6-7 (137)
Biogas	2	-	45 (90)
flydende biobrændsler	-	-	22 (47)
Solvarme	0	4	40
Solceller	0	4	25
Vindkraft	3	32	90
Netto elimport	14	0	0
Total	776	573	222 (292)

\*) Energistyrelsens tal

Noter til tabel 6.3:

En betydelig del af det lysegrønne scenaries biomasseforbrug går via industriel forgasning til brændselsceller. Dette er også en mulighed i det mørkegrønne scenarie, men det er her valgt i stedet at producere biogas ved hjælp af biologiske metoder. Anvendelsen af biogassen kan dog ske med samme konverteringsteknologier som i det lysegrønne scenarie, og med samme lagringsfordele. Anvendelse af varmepumper til

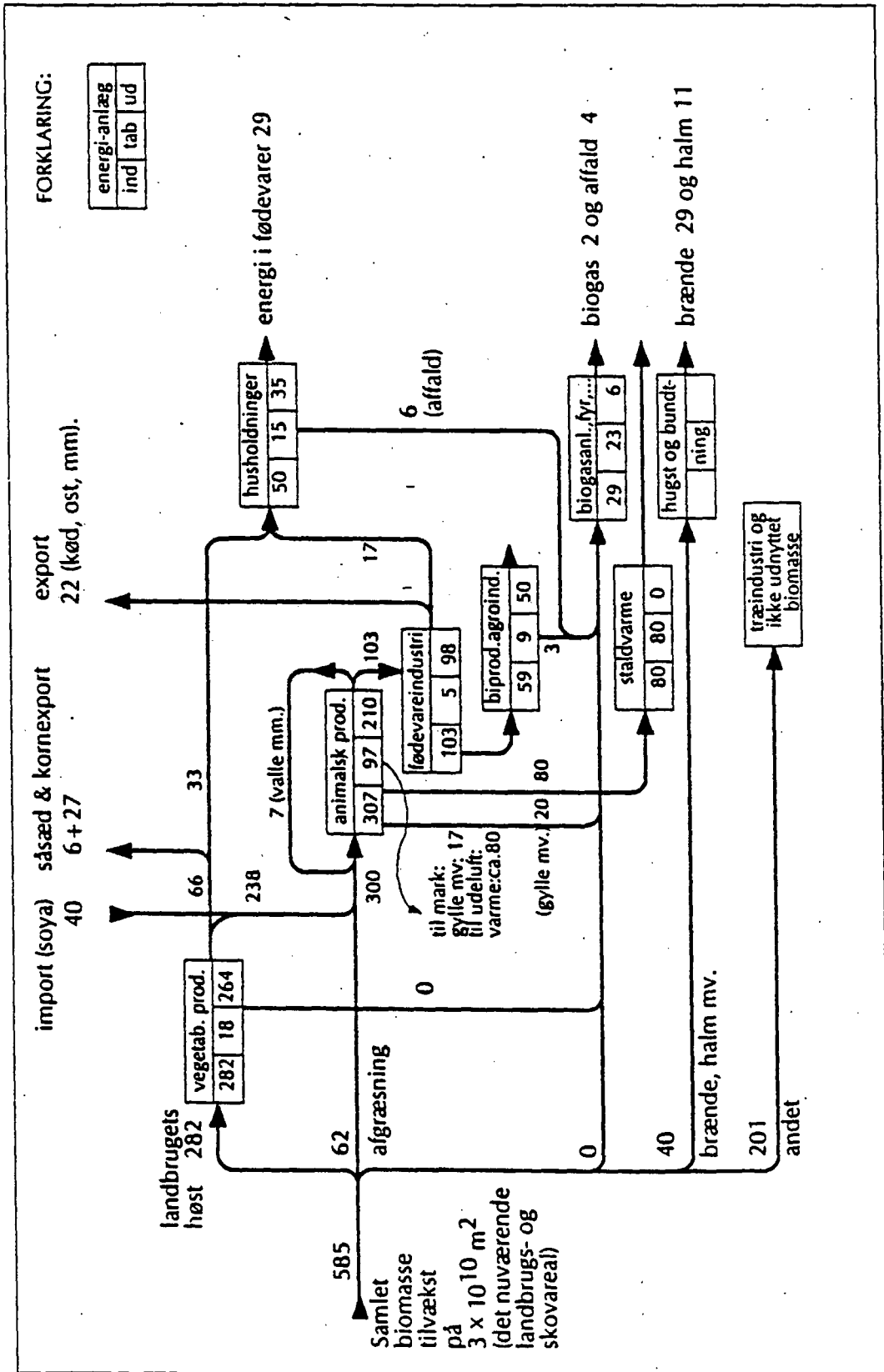
dækning af varmebehov, baseret på biobrændsel, forudsættes også at kunne finde sted, hvis varmebehovet overstiger den umiddelbart tilgængelige varmemængde i systemet.

Tallene i parentes for det mørkegrønne scenarie er de mængder af biomasse-energi, der brutto anvendes til produktionen af biogas eller flydende olie-substitutter (ialt 137 PJ pr. år, som kan sammenlignes med det lysegrønne scenarie).

Varme fra omgivelserne og fra landbrugets besætninger er ikke medtaget i tabellen.

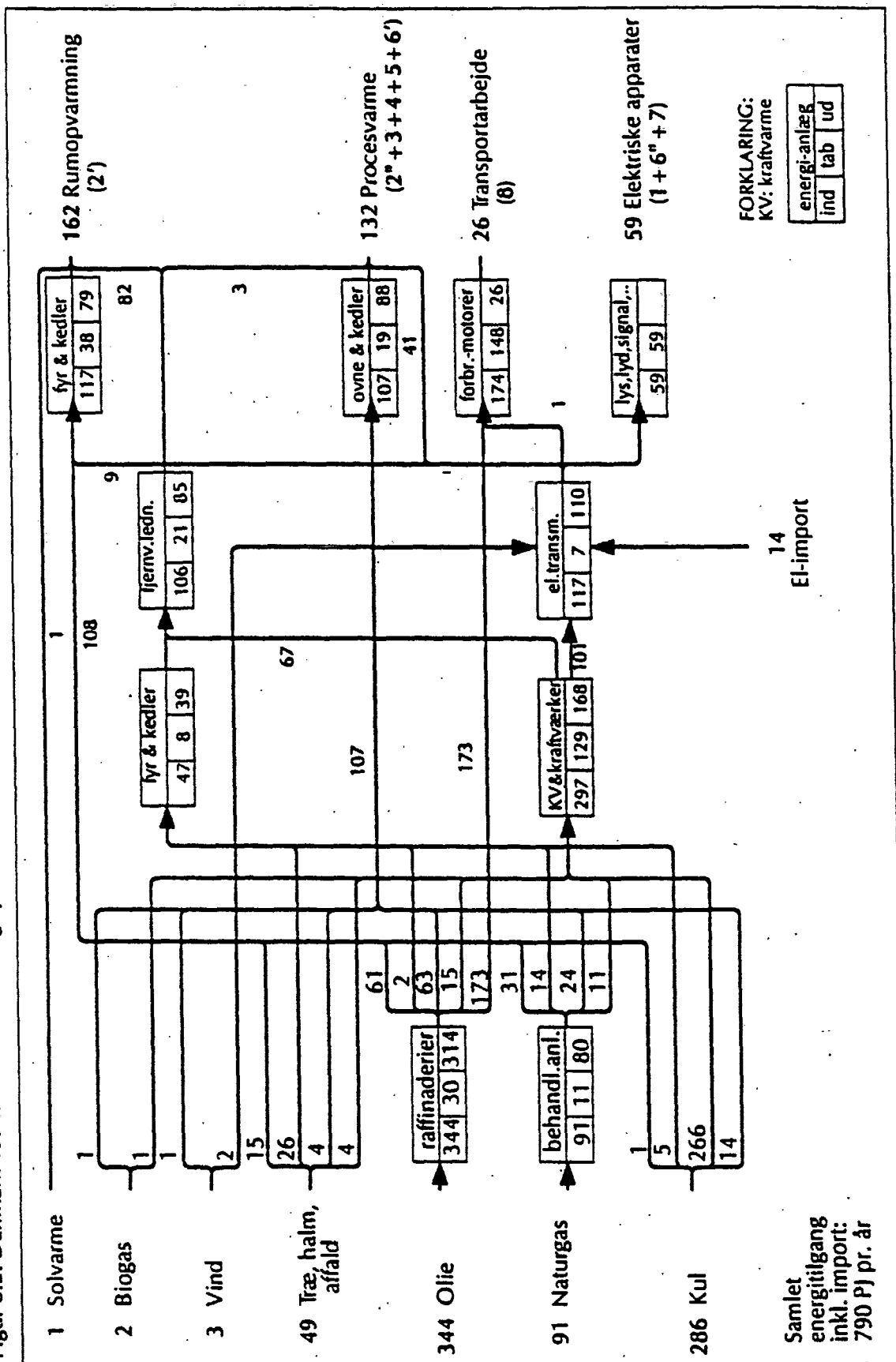


Figur 6.1. Danmark 1992. Opbygningen af nuværende biomasse-sektor (indirekte energiinput gennem kunstgødning, maskiner, transport mv. er ikke medtaget her). Enheden for figurens energistrømme er PJ pr. år

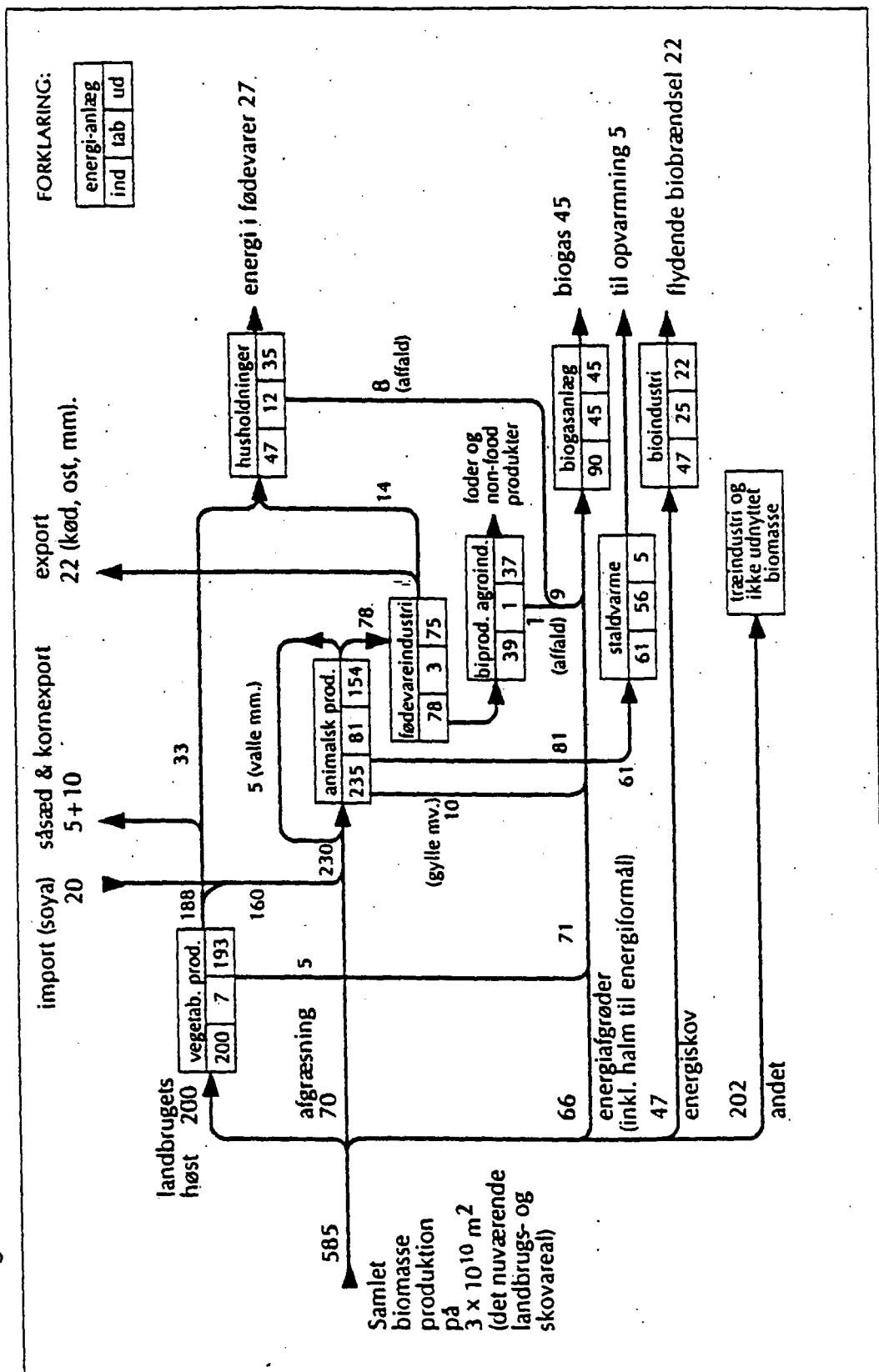


(INDEHOLDER SKØN OG USIKRE TAL)

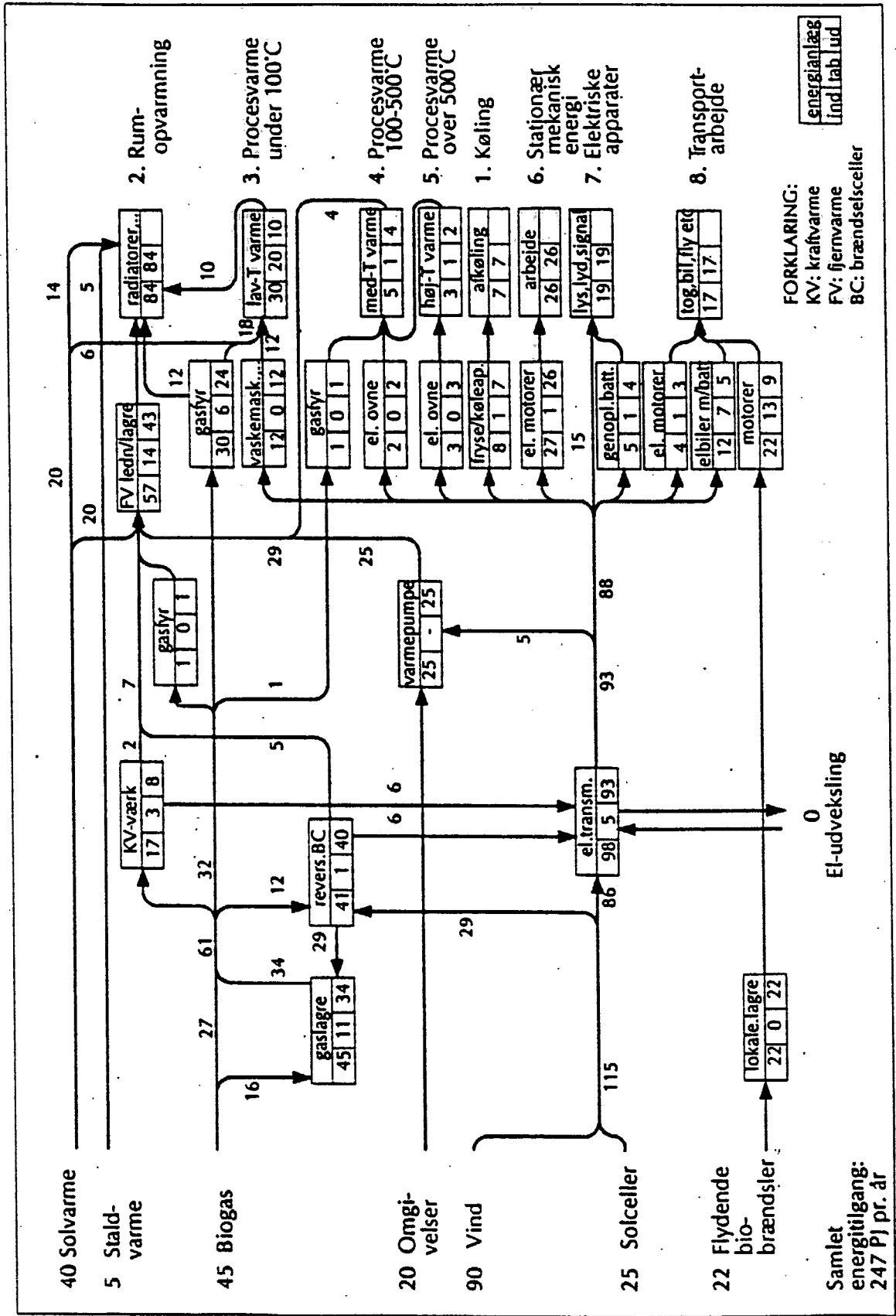
Figur 6.2. Danmark 1992. Nuværende energisystem. Befolkning 5.1 M. Energistrømme i PJ pr. år.



Figur 6.3. Danmark 2030. Scenarie for biomasse-sektoren (indirekte energiinput gennem kunstgødning, maskiner, transport mv. er ikke medtaget her). Enheden for figurens energistømme er PJ pr. år.



Figur 6.4. Danmark 2030. Scenarie baseret alene på vedvarende energi. Befolkning 5.3 M. Energistrømme i PJ pr. år.



(INDEHOLDER SKØN OG USIKRE TAL)

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## **THE USE OF LIFE-CYCLE ANALYSIS TO ADDRESS ENERGY CYCLE EXTERNALITY PROBLEMS**

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### **INTRODUCTION**

The work reported in the present communication is based on several years of consultancy to the OECD regarding the methodology of life-cycle analysis, followed by implementation studies performed for the Danish Department of Energy and as a contractor for the the Fuel Cycle Externality Project of the European Community Joule II Programme. The work also underlies the author's work as a member of the IPCC (Intergovernmental Panel on Climate Change) working group II and consultant to working group III.

### **DEFINING LIFE-CYCLE ANALYSIS**

Life-cycle analysis (LCA) is a method, by which it is possible in principle to assess all direct and indirect impacts of a technology, whether a product, a system or an entire sector of society. LCA incorporates impacts over time, including impacts deriving from materials or facilities used to manufacture tools and equipment for the process under study, and it includes final disposal of equipment and materials, whether involving reuse, recycling or waste disposal.

Whereas product LCA is used by manufacturers and regulators to select the optimal one among different products serving the same purpose, energy system and energy policy LCA may be used to handle greenhouse emission issues in a way consistently embedding the global warming issue within other environmental and social issues. In case not just individual energy systems, but national and regional energy policies have to be assessed, the LCA must be based on an assumed transition to a scenario for future energy supply, transmission, conversion and use.

These remarks define the issue of the present paper, linking issues of global development, scenarios for future energy use, and finally political assessment with the assistance of LCA as a tool.

### **IDENTIFICATION OF LIFE-CYCLE IMPACTS**

The impacts that one would like to include in an LCA are likely to depend on time and place of assessment. However, in broad terms, they may be grouped into the following categories (Sørensen, 1993b):



**Economic impacts such as impacts on owners economy and on national economy, including questions of foreign payments balance and employment distribution.**

Economy is basically a way of allocating scarce resources. Applying economic assessment to an energy system, the different payment times of different expenses have to be taken into account, e.g. by discounting individual costs to present values. This again gives rise to different economic evaluations for an individual, an enterprise, a nation, and some imaginary global stake holder. One possible way of dealing with these issues is to apply different sets of interest rates for the above types of actors, and in some cases even a different interest rate for short-term costs and for long-term, inter-generational costs, for the same actor.

Precursors to these kinds of economic evaluation are the separate private economy (sometimes referred to as direct economy) and national economy accounts often made in the past. The national economy evaluation includes such factors as import fraction (balance of foreign payments), employment impact (i.e. distribution between labor and non-labor costs), and more subtle components such as regional economic impacts.

**Environmental impacts, e.g. land use, noise, visual impact, local pollution of soil, water, air and biota, regional and global pollution and other impacts on the Earth-atmosphere system, such as climatic change.**

Environmental impacts include a very wide range of impacts on the natural environment, including both atmosphere, hydrosphere, lithosphere and biosphere, but usually with the human society left out (but to be included under the heading social impacts below). Impacts may be classified as local, regional and global.

At the resource extraction stage, in addition to the impacts associated with extraction, there is the impact of resource depletion. In many evaluations, the resource efficiency issue of energy use in resource extraction is treated in conjunction with energy use further along the energy conversion chain, including energy used to manufacture and operate production equipment. The resulting figure is often expressed as an energy pay-back time, which is reasonable because the sole purpose of the system is to produce energy, and thus it would be unacceptable if energy inputs exceeded outputs.

In practise, the level of energy input over output that is acceptable depends on the overall cost, and should be adequately represented by the other impacts, which presumably would become large compared with the benefits, if energy inputs approached outputs. A low extraction efficiency can well be accepted, if the resource is free or nearly free (e.g. solar radiation). In other words, energy pay-back time is a secondary indicator, which should not itself be included in the assessment, when the primary indicators of positive and negative impacts are sufficiently well estimated.

Also issues of the quality of the environment, as seen from an anthropogenic point of view, should be included here. They include noise, smell and visual impacts associated with the cycles in the energy activity. Other concerns include the preservation of natural flora and fauna.

**Social impacts, related to satisfaction of needs, impacts on health and work environment, risks, impact of large accidents, institutions required.**

Social impacts include the impacts from using the energy provided, which means the positive impacts derived from services and products arising from the energy use (usually with other inputs as well), and some negative impacts associated with the energy end-use conversion. Furthermore, social impacts derive from each step in the energy production, conversion and transmission chain. Examples are occupational health issues, work environment, job satisfaction, and risk, including the risk of large accidents. Another area of po-

tential social impacts are in the institutional setup of the systems providing energy of a certain kind: types of organizations, financing schemes, and so on. Some of these issues connect to those mentioned below under the heading "political impacts".

**□ Security impacts, including both supply security and also safety against misuse, terror actions, etc.**

Security can be understood in different ways. One is supply security, and another the security of energy installations and materials, against theft, sabotage and hostage situations. Both are relevant in a life-cycle analysis of an energy system. Supply security is a very important issues for those energy systems depending on fuels unevenly spread over the planet. Indeed, some of the most threatening crises in energy supply have been related to supply security (1973/74 oil supply withdrawal, 1991 Golf War).

**□ Resilience, i.e. sensitivity to system failures, planning uncertainties and future changes in criteria for impact assessment.**

Resilience is also a concept with two interpretations: One is the technical resilience, including fault resistance and parallelism, e.g. in providing more than one transmission route between important energy supply and use locations. Another is a more broadly defined resilience against planning errors (e.g. resulting from a misjudgment of resources, fuel price developments, or future demand development).

A more tricky, self-referencing issue is resilience against errors in impact assessment, assuming that the impact assessment is used to make energy policy choices. Many of the resilience issues are connected to certain features of the system choice and layout, including modularity, unit size, and transmission strategy. The possible use of an impact awareness escalation rate has been suggested by Rabl (1994).

**□ Development impacts (e.g. consistency of a product or a technology with the goals of a given society).**

Energy systems may exert an influence on the direction of development a society will take, or rather may be compatible with one development goal and not with another goal. These could be goals of decentralization, goals of concentration on knowledge business rather than heavy industry, etc.

For so-called developing countries, clear goals usually include satisfying basic needs, furthering education, and raising standards. Goals of industrialized nations are often more difficult to identify. Often emphasis on agriculture, industry and export are ingredients in the strategies of developing countries. The positive or negative impact of a given energy system on these goals constitute development or political impacts.

**□ Political impacts include e.g. impacts of control requirements, and on openness to decentralization in both physical and decision-making terms.**

There is a geo-political dimension to the above issues: Development or political goals calling for import of fuels for energy may imply increased competition for scarce resources, an impact which may be evaluated in terms of increasing cost expectations, or in terms of increasing political unrest (more "energy wars").

The political issue also has a local component, pertaining to the freedom or lack of freedom of local societies to choose their own solutions, possibly different from the one selected by the neighboring local areas.

It is clear that a list of the kind given above is open-ended, and that some impacts will never become quantifiable. This raises new problems of how to present and use an LCA, which would typically produce a list of impact estimations, some of which quantified and some not, and with the quantifiable impacts often given in

quite different units (e.g. tons of sulphur dioxide, number of work accidents, capital cost of equipment).

On the other hand, weighing of incommensurable impacts is precisely what the political decision-making process is about. If the LCA impacts of each system could be expressed as a single number, one might as well let the computer choose the solution with the smallest negative impacts. But because the impacts are of different kinds, our value systems and preferences, as well as some democratic playing rules are needed, in order to reach an agreement on the choice of system. This raises new problems of how to present and use an LCA, which would typically produce a list of impact estimations, some of which quantified and some not, and with the quantifiable impacts often given in quite different units (e.g. tons of sulphur dioxide, number of work accidents, capital cost of equipment).

One philosophy is to try to convert all impacts into monetary values, i.e. replace the sulphur dioxide amounts with either the cost of reducing the emissions to some low threshold value (avoidance cost) or alternatively an estimated cost of the impacts: hospitalization and workday salaries lost, replanting cost of dead forests, restoration of historic buildings damaged by acid rain. Accidental death would be replaced by the insurance cost of a human life, and so on (damage costs). Unavailability of numbers has led to the alternative philosophy of interviewing cross sections of affected population on the amount of money they would be willing to pay to avoid a specific impact or to monitor their actual investments (revealed preferences, willingness to pay). Such a measure may change from day to day, depending on exposure to random bits of information (whether true or false).

All of these methods are deficient, the first by not including a (political) weighing of different issues (e.g. weighing immediate impacts against impacts occurring in the future), the second by doing so on a wrong basis (influenced by peoples knowledge of the issues, by their accessible assets, etc.). The best alternative may be to present the entire impact profile to decision-makers, in the original units and with a time-sequence indicating when each impact is believed to occur, and then to invite a true political debate on the proper weighing of the different issues.

The difficulties encountered in using LCA in the political decision-making process have been partly offset by the advantages of bringing the many impacts often disregarded (as "externalities", meaning issues not included in the economic analysis) into the debate. It may be fair to say that LCA will hardly ever become a routine method of computerized assessment, but that it may continue to serve a useful purpose by focussing and sharpening the debate involved in any decision-making process, and hopefully help increase the quality of the basis information, upon which a final decision is taken, whether on starting to manufacture a given new product, or to arrange a sector of society (such as the energy sector) in one or another way. Examples of actual energy system LCA's are given towards the end of the paper.

### THE CURRENT DEVELOPMENT SCENE

The recent collapse of a number of conservative communist regimes with a sterile top-down control structure and inherent conservatism has led to a reassessment of development models, both in currently industrializing countries and in economies yet to choose their path of development.

There has been a surge of efforts to reinstate and spread a variety of liberalism based upon nineteenth century crude versions of market controlled economies with minimal roles accorded to governments. This situation makes it very important for leaders responsible for national development strategies to keep their heads cold and take a more comprehensive view of the issues.

An alternative development model used to be suggested by the Scandinavian countries. Central in the Scandinavian way of thinking was a necessity for looking at things with global eyes, and an ability to feel uncomfortable when confronted with a strongly unequitable distribution of assets and opportunities. However, the set of values promoted by particularly the United States of America have recently set themselves through in many other parts of the world, including Scandinavia. The advocates are often economists basing their advice to decisionmakers on a partial model of society, and yet pretending that the prevailing economic theory is a universally valid science. In reality it hardly deserves to be called a science, but rather constitutes a codification of some particular views regarding social power structures, according e.g. to Blatt (1983) and Eichner (1983).

In order to develop more comprehensive alternatives to the atavistic economic descriptions of current development options, it is an urgent priority to look for consistent alternative social and economic models, which on one hand avoid inviting to the power concentration and the curtailment of development initiatives that accompanied the transition from socialism to communism, and on the other hand offer a clear break with the primitive liberalism dominating at present.

### **The third way**

The basis for an alternative way of shaping national policies may involve a technique known as the scenario method. It basically consists in selecting a few of the possible futures, chosen on the basis of having spurred an interest in the population and by reflecting different values held in a particular society.

As the next step, these futures have to be modelled, with emphasis on the issues deemed particular important: better social conditions, less polluting energy systems, environmentally sustainable processes, societies offering human relationships within a preferred frame, and so on. During this process one must keep in mind, that models are simplified and necessarily inaccurate renditions of reality, and have to be treated accordingly. Models are essentially frameworks for discussion.

One would next have to discuss the consistency of the elements in the models, e.g. as regards sustainability, resource availability, and consistency between different aspects of the scenario. And finally discuss possible paths from the present situation to the scenario future. This would be done for each scenario proposed, as part of an assessment which involves the full apparatus of political debates and decision-making processes.

Central questions to address are who should propose the scenarios and who should stage the debate and decision process. There are clearly many possibilities for manipulation and unfair representation of certain views. Whether a democratic process can be established depends on the level of education and understanding of the decision process, by the citizens of a given society, as well as on the tools used for debate, including questions such as fairness of and access to media. Many developed countries have a tradition for broad social debates, but even in such countries, there are also clear efforts by interest groups or sitting governments to take over the communication means and distorting the process in favour of their own preferred solutions. These institutional questions have to be part of any realistic proposal for a new way of approaching development issues (cf. Figure 1).

## **AN EXAMPLE OF SCENARIO TECHNIQUE APPLIED TO ENERGY PLANNING**

In order to illustrate the issues involved, scenarios of energy demand are first presented from a global perspective, and then exemplified for Denmark in order to present an already worked out energy system construction amenable to assessment by life-cycle analysis.

## Demand models

The bottom-up approach for determining energy demand (Sørensen, 1981b; 1984; 1988) is based on a model in which all basic needs are to be covered (food, shelter, human interaction), and furthermore a broad selection of secondary needs, that may be selected differently by different societies and by different individuals (activities, relations, possessions). The needs are then analyzed in terms of energy inputs, recognizing that in many cases, the same products and services can be produced in different ways, characterized by highly different inputs of materials and energy (Figure 2).

The outcome of this analysis is, that over a broad range of secondary need's selections, geographical locations (important for heating and cooling needs) and settlement types (from dense cities to dispersed living), the required average flow of energy inputs are in the range of a half to two kW per capita, except for extremely cold climates. This assumes using the best technology known at present. Fifty or a hundred years ago, the numbers would have been higher (if the same needs could have been delivered), and in the future, new technological breakthroughs may make the numbers lower. Particularly as regards the low-temperature heat use, a wealth of options are available, including heat pumps and heat cascading.

Figure 3 gives an overview of energy flows, divided on energy qualities and broad classes of activities. Note that the bottom-up approach implies, that the desired human activities constitute the driving force, and that production of goods and services becomes a derived quantity, the size of which depends entirely on the specification of needs. The societies are not assumed to produce goods blindly, in the hope that a demand can be created, once the goods are brought to the market. Again this is a Scandinavian way of looking at the production process, very different from the primitive market picture prevailing in e.g. Anglo-Saxon countries. However, different societies may place emphasis on different types of production (basic materials, consumer goods, agricultural products, knowledge-based services, and so on). This is what gives rise to the wide ranges of possible energy use in the activity sectors.

Figure 4 gives a specific example of the demand matrix of Figure 3, to be used for the energy supply model considered in the following chapter and pertaining to a scenario for Denmark attempting to catch some important traits of Danish preferences (Sørensen, 1994).

Among the energy demand models that could be considered, there would generally be growth and saturation models. By this is understood growth and saturation in services and production, which again may or may not lead to growth in energy demand, depending on the cost of energy systems as compared with other factors in the economy. Historically, short periods of growth have been followed by long periods of saturation on various levels, both for production and energy use (Sørensen, 1979).

Present arguments for or against growth both refer to third world development: One side claims that economic growth will make the cake to share larger and everybody happier, while the other side says that growth will create stronger competition for scarce resources, and that will hurt the regions trying to develop. The actual development trends over the latest decades in some areas support the second view, and it is not difficult to argue in general terms, that global claims on the resource base do not seem to promote equity, but certainly helps in creating hostility and cause warfare (problem of fundamentalist movements, oil wars).

It is important to stress, that one can have growth in the economic sense without the associated growth in resource usage: If the main growth is in intellectual activities and services, the physical growth can be zero or negative, while the economy may continue to flourish, remembering that economic indicators such as GNP only measure the level of *activity*. The scenario depicted in Figures 3 and 4 assumes a future society with increased emphasis on environmental sustainability, low and efficient resource usage and growth in those activities expected in an information-society (Porat, 1977; Valaskakis and Fitzpatrick-Martin, 1980).

### **Bottom-up construction of energy systems**

Once the energy demand structure is given, the modeler's task is to construct a supply, conversion and delivery system capable of satisfying the demand at the end-users. The selection of the system depends on the technologies available, but also in some cases on preferences between different system layouts, of which one is not clearly superior to all the other ones. Typically, the life-cycle impacts of different types of system are so different, that some groups in the society have clear preferences for one solution and feel that they would not like to live with some of the other solutions, while other groups in the society may feel just the opposite way.

In such cases, one could possibly give high priority to options involving a decentralization, that would allow different subgroups in a society to select different solutions, rather than going for centralized solutions bound to make some fraction of society unhappy. That this is possible hinges on the recent development of decentralized solutions without cost penalties, i.e. that technology has entered a stage, where the economy of scale is less important than it was some decades ago.

The technique for constructing the energy system may consist in tracing the system back from the end-user, but as it will become clear, this is not always possible, and some tracking back and forth between supply and demand may be required. At each end-user, one may first consider the options for local energy production, such as solar heat, solar cells, building-size fuel cells, and so on. When intermittent production is included, the question of load-matching and energy storage has to be considered. Some such storage may be located at the end-user. Current examples are batteries for portable equipment and heat stores for solar thermal collection systems. In a wider perspective, also load-management has to be considered, such as deference of non-urgent tasks, within time-limits accepted by the user and possibly reflected in her/his cost of energy.

On the supply side, there might be installations characterized by a large fraction of the cost tied up in equipment (e.g. wind turbines, photovoltaic panels), but for which the operating cost is very small. Such equipment should have priority, once it is part of the system, and if the energy generation is also intermittent, these installations have to be dispatched before others that may be regulated. This means, that such priority equipment has to be considered up front, also in cases where it is not located near the user, and thus transmission and any further conversion to other energy forms should be determined at this stage. There may also be options for central storage in the system, that can take care of surplus production from priority sources. If not, any overflow must be exported or will be lost.

In principle, the modeler works backwards from the end-user over transmission and conversion equipment to the primary energy source inputs, but with the above-mentioned priority sources as bound options. In some systems, the delivery paths in place (gas, electricity and heat transmission lines) determine which energy flows can be directed at particular groups of end-users, but in many cases, there would be more than one option for generating the various energy forms then demanded. This defines the dispatch problem, where a routine must be found for selecting the succession of generating equipment and feeding energy sources, that will be employed at any given moment.

This selection may be based on a ranking of the sources (e.g. in terms of generating costs), but often there is more than one solution satisfying any simple criteria. This is certainly the case, if the system comprises storage and import/export options in various places between supply and demand. One of the criteria to consider is security of supply, meaning that one minimizes the risk that e.g. stores are empty when they are unconditionally needed (especially relevant for systems with a high fraction of intermittent sources).

It is important to distinguish between systems modelling aiming at proposing an optimal system layout, i.e.

which components to build, and modelling aimed at utilizing a given system optimally, by selecting the best dispatch pattern. These two aspects may be combined in a dynamic simulation of the system, where one tries to identify the signals, that should lead to decisions to add components to the system (or phase out components), with given lead times between decision and operability of the new components.

Figures 5 and 6 give an overview of a preliminary version of a scenario for a future Danish energy system based upon renewable energy sources and the demand scenario of Figure 4 (Sørensen, 1994).

It assumes a wind contribution based on a number of 2 MW turbines similar to the present number of smaller machines, and that roughly a quarter of all buildings have solar thermal or photovoltaic collectors. The contribution from biomass include gas and liquid fuels, and is based on the already started transition in the Danish agricultural sector, where a smaller area will be used only for food production, yielding however the same export of refined products but a balance considered more healthy between animal and vegetable products for indigenous consumption. The biomass for energy purposes are partly derived from better utilization of current "waste", partly from dedicated energy crops. However, the total cultivated area is not expanded from its present value.

Figure 5 details the flows in the agricultural sector, while Figure 6 treats the rest of the system leading to the end-users. The scenario is preliminary, as the dynamical simulation of the supply-demand matching has not yet been performed, but only the overall balancing of flows. However, it gives an example of a system taking advantage of the current transmission network for electricity, gas and heat, and at the same time removing fossil fuel inputs and their greenhouse emissions over a 30 year period, with minimum requirement for long-term energy storage (although the system does comprise heat stores, gas stores in aquifers and salt domes, and a little electricity storage capacity in batteries and compressed gas stores).

It is assumed that the interconnection with the European power grid will take care of any further mismatch between electricity production and local demand. This involves some imports and exports, judged to be beneficial to both partners in the exchange. For example, the exchange with countries such as Norway possessing large seasonal hydro stores allows for taking care of day-to-day mismatch, while adding to the resilience of the Norwegian system towards coping with particular dry years, a function which today is taken care of by the Danish fossil fuel power stations (Sørensen, 1981).

In the transportation sector, the scenario for year 2030 assumes, that only electric vehicles are allowed in cities, and that long-distance transport of goods and people will be based on biofuels.

## IMPLEMENTATION OF LIFE-CYCLE ANALYSIS FOR RENEWABLE ENERGY SYSTEMS

The examples of LCA assessment given below is for selected energy technologies, such as wind and photovoltaics, characterized by near absence of climatic effects (depending on where the materials used and energy inputs to manufacturing comes from). For comparison, an assessment of coal-based power is added, with its strong climatic impacts. One purpose of LCA is of course to provide a full impact overview, such that the higher direct cost of many renewable energy solutions may be weighed against the lower indirect impacts. An LCA assessment of a complete future scenario of energy supply, such as the one given in the previous section for Denmark, is underway but will not be reported here. Now a few practical remarks:

In a practical implementation of LCA, each impact is initially presented in units relevant for the category in question. In presenting the impact profiles derived in this way to decision-makers, a scale of -1 to 1 may be used, because the weighing of incommensurable impacts will anyway involve the decision-maker's choice of weight factors. It may seem, that the accuracy of this approach is lower than if physical units (such as death

per kWh or kilos of SO<sub>2</sub> per kWh) had been used. However, this is not necessarily the case, since the precision with which the physical data can be given is quite consistent with a fairly coarse indication, allowing a resolution of perhaps less than ten levels in the range of impacts being evaluated as negative over neutral to positive. It is also possible to include non-linearities in the criteria adopted. At the extreme these could be the labelling of some impacts as unconditionally unacceptable (Sørensen, 1993b).

## WIND TURBINES AND SILICON SOLAR ROOFTOP MODULES

The wind turbine analysis (Sørensen, 1993c) presented in Figure 7 pertains to Danish turbines currently produced and locally installed. It is realized that several of the impacts exhibit a dependence on the natural, social and human setting. Thus one should be careful in transferring data to other settings than the Danish one. The penetration of wind power in the Danish electricity system is currently 4-5%. If penetrations above some 20% were achieved, the question of energy storage would have to be addressed. However, given the strong international links, e.g. to the Norwegian hydro system based on annual storage cycles, the cost of dealing with the variability of wind energy production could turn out to be very low (Sørensen, 1981c).

The manufacture of photovoltaic cells is today barely suitable for generic assessment. Some mass-scale production is taking place, but the technology continues to change, as it has to in order to approach a price level catering to major market segments such as bulk power production. Furthermore, the worldwide industrial capacity is currently not fully used, and this slows down an introduction of improvements that are already identified and ready for implementation. Some of these improvements are known to lead to substantial improvements in conversion efficiency, while others reduce the manufacturing cost and at the same time reduce the environmental impacts of cell and module manufacture.

The life-cycle analysis presented in Figure 7 (Sørensen, 1993c; Watt and Sørensen, 1993) pertains to the current manufacturing technology for silicon-based cells. These comprise the substantially different technologies of crystalline and amorphous cells, and of solid or thin-film techniques. When impacts depend on these differences, it will be pointed out. Furthermore, there are several differences between the impacts of modules for centralised power plants, and those aiming at decentralised use, integrated into building structures such as roofings. One of these differences has to do with the possibility of using concentrator cells and tracking devices, while other obvious differences have to do with area use. Also the possible modularity of electricity conditioning equipment such as inverters may differ.

The present analysis assumes non-concentrating cells in modules mounted on individual buildings. Cell and module fabrication is assumed to take place in the country using the modules, and the penetration of the technology plus the structure of the residual electricity supply system is assumed to be such, that no particular requirements for energy storage arise in conjunction with the photovoltaic panels. The main steps in the life-cycle of photovoltaic devices are depicted in Figure 8.

### Impacts

The overall cost of producing wind energy in Denmark is currently about 35 øre/kWh (5 US cents per kWh), with O&M constituting an average of 7 ø/kWh (1 c/kWh) out of this, averaged over an assumed 20 year lifetime. Because the capital cost is dominating, there is much less uncertainty in cost after the turbine is installed, than there would be for a fuel-based system. The import fraction of the capital cost is 28%, that of the running cost 15%. The employment factor is about 3 (fulltime equivalent per million Danish Kr. spent). Labour is considered a negative impact in Figure 7, but it might be viewed as a positive attribute by some societies (with activity deficiency or inefficient distribution of wealth), especially in times of unemployment.



In any case, creating jobs within a society is often viewed as preferable compared with creating jobs abroad.

Current cost of photovoltaic power is about 40 US cents per kWh, but expected to fall to around 10 c/kWh early in the next century. Of the 40 c/kWh, about 25 c derive from module capital cost and 1 c from O&M, the rest being balance of system (BOS) capital cost. The projection would be for around 6 c/kWh for the modules and 3 c/kWh for the BOS in the rooftop mounted case, assuming integrated PV-building elements or thin-film modules glued onto a cheap substrate building element. No installation cost apart from electric connection is included, assuming that mounting costs are the same as for other roofing elements. The national economy items are similar to those of wind turbines, except for the higher labour content associated with the higher cost.

Danish wind turbines are placed both in park configurations and individually. The land between them and right up to the towers may be used for agriculture, so that the largest cost in terms of land-use is often the access roads needed for service purposes. Typical values are 10 m<sup>2</sup> per kW rated power. Land resources may be returned after decommissioning.

The mechanical noise from Danish wind turbines is below current minimum regulatory limits (35dB(A) in the audible range, and about 70 dB(A) for infrasound) a few rotor diametres away from the turbine. Aerodynamical noise from the blades is similar to that of other structures or vegetation. Telecommunication interference has been studied and found similar to that of static structures (e.g. buildings).

The extraction of power from the wind has a slight influence on the microclimate below and behind the turbines, but otherwise the pollution associated with the operation of wind turbines is limited to minor issues such as oil used for greasing. The main potential source of pollution is the manufacture and maintenance operations, which are subject to the usual industrial regulation. The work environment at manufacturers of windmill components is similar to that of other equipment manufacturers, while the work environment for tower building, assembly and maintenance is similar to that of work in the building industry, with lots of open air activities and scaffold work at a height. With proper safety precautions, such work is generally offering a varied and challenging environment.

Health problems are primarily present in the industrial part of manufacture, including in particular the use of epoxy resins in blade manufacture. Modern production lines have confined this step of production to closed spaces with fully automated facilities, implying that employees only do control-room work, and that the risk of exposure to harmful chemicals is basically an accident risk. 18 years of blade manufacturing experience has proven that the accident risk can be kept extremely low.

The use of dedicated land resources is zero for rooftop mounted solar panels. Silicon is abundant everywhere, in the form of silicon dioxide, but as for any mining operation, its extraction may affect the natural environment. The operation of solar panels is without noise or smell, but the integration of panels in buildings does require architectural skills in order to produce acceptable visual impacts.

The industrial handling of silicon, throughout the steps of production, all involve potential pollution of the environment, unless all materials used are accounted for and recycled (Watt and Sørensen, 1993). The processes involved are typical of many chemical/mechanical industries or particularly of the semiconductor industry, so one may use data from that industry in the analysis.

Social benefits derive from the electricity produced. Both Wind and photovoltaic energy can have impacts on the infrastructure of the electricity supply system, because of the dispersed mode of production, that may lead to reduced demands for the power transmission.

The work environment for solar cell manufacture involves the risk of exposure to a range of dangerous chemicals. Most have analogies in the semiconductor industry (Watt and Sørensen, 1993). On the other hand, few impacts are expected during operation of PV systems or their retirement.

Security of supply from both wind turbines and solar cells is generally high, with the qualifications related to the variability of the resource. The modular nature of the systems make individual failures less important. Because of the short time lag between deciding to build the system, and its operation, the renewable energy technologies considered have much less sensitivity to planning errors (e.g. wrong forecast of future loads) and changes in criteria used for selecting technology, than systems with several years lag between decision and operation.

For both wind and particularly for building-integrated solar cells, a decentralized decision process and local control are readily possible.

### COMPARISON WITH A CONVENTIONAL FUEL-BASED SYSTEM

The impact profiles of Figure 7 are in many ways typical of renewable energy systems. It is therefore relevant to place them in perspective, by comparing them to the profiles pertaining to conventional fuel-based systems. Figure 9 shows such a profile, for electric power produced by a large coal-fired plant. Data pertains to the Danish level of particulate removal, SO<sub>2</sub> scrubbing etc (Sørensen, 1993c). Preliminary results of a fuel externality study within the EU Joule II program is indicated, in those cases where numerical values have been obtained (European Union, 1994).

The profiles exhibit, in addition to the wellknown differences between fuel-based and renewable energy systems, in economic impacts, a number of stark differences in all other impact areas, which strongly favours the renewable energy solutions.

### CONCLUDING REMARKS

The purpose of the present article has been to demonstrate some of the working methods presently characterizing the field of energy and environment, and to place them in the context of the IPCC work on greenhouse effect mitigation and development. This in particular involves the identification of assessment methods, that retain not only conventional economic, but also environmental and social impacts from energy activities. The scenario methods linked to LCA are offered as the likely best candidates for political assessment in this field.

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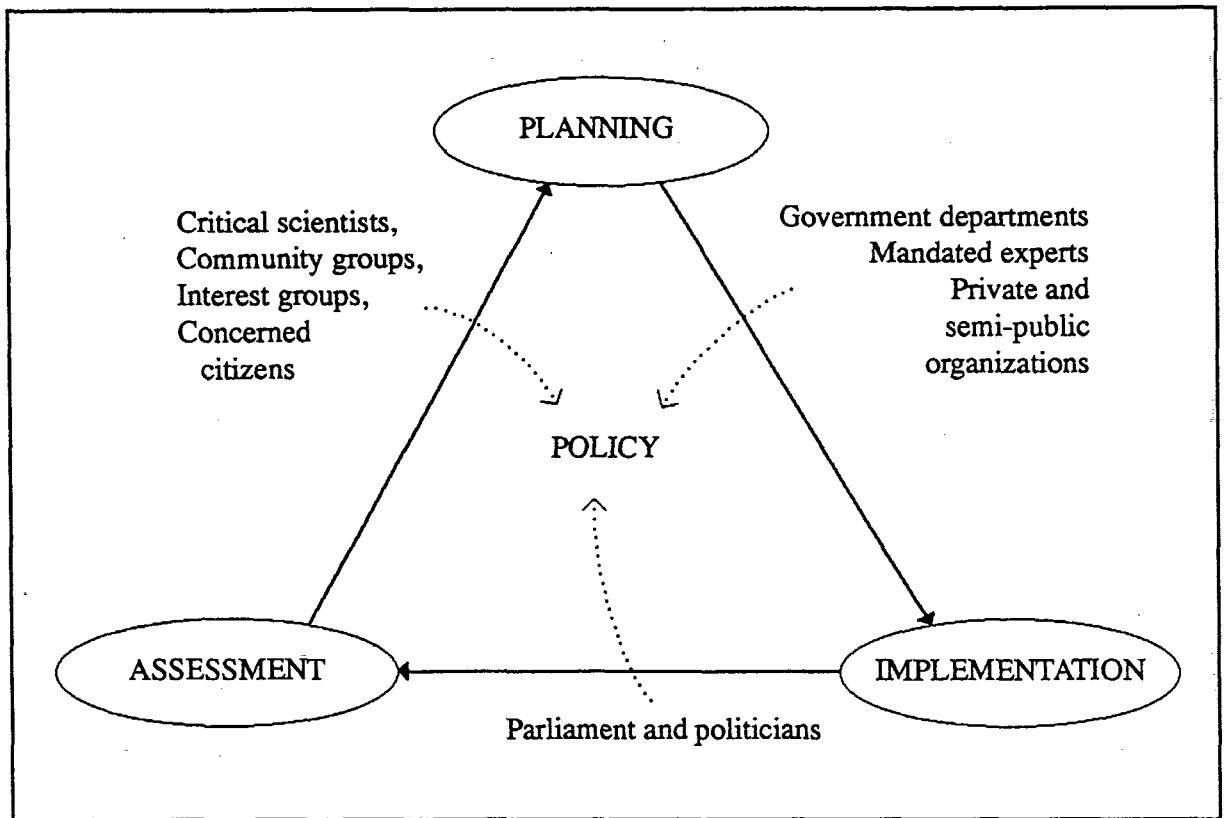


FIGURE 1. The actor triangle, a model of democratic planning, decision-making and continued assessment (Sørensen, 1993).

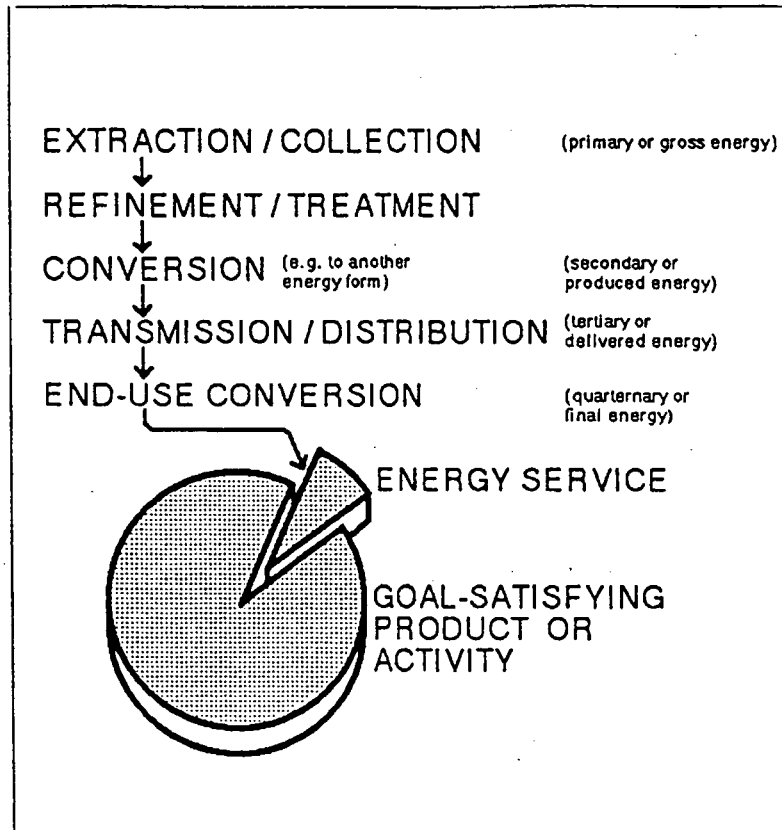


Figure 2. Energy conversion chain (Sørensen, 1988).

FIGURE 3. Scenario for the rate of end-use energy needed for satisfying goals in different societies at different geographical locations (W per cap) (Sørensen, 1984; 1988; 1994).

	1. Cooling & refrigeration	2. Space heating	3. Process heat under 100°C	4. Process heat 100-500°C	5. Process heat over 500°C	6. Stationary mechanical energy	7. Electric appliances	8. Transportation work	9. Food energy	TOTAL
A. Biologically acceptable surroundings	0-24	0-1500	0	0	0	0	0	0	0	0-1524
B. Food and water	14-24	0	15	2-6	0	0	0	0	120	151-165
C. Security	(0)	(0)	0	0	0	(0)	0	(0)	0	(0)
D. Health	0	0	80-150	20-40	0	0	(0)	(0)	0	100-190
E. Relations, leisure	(0)	(0)	0	0	0	0	10-60	25-133	0	35-193
F. Activities:										
Construction	0	0	0	0	0	30-60	0	7-15	0	37-75
Trade, service and distribution	1-8	0-600	0-12	0	0	6	10-20	30-70	0	47-716
Agriculture	0	0	2-12	0	0	3-6	0-2	3-6	0	8-26
Manufacturing industry	1-16	0-600	10-100	20-70	12-30	20-60	15-30	7-15	0	85-921
Raw Materials and energy industry	0	0	0-30	0-20	0-250	0-170	0-30	0-20	0	0-520
Education	0-2	0-160	0	0	0	0	1-2	0	0	1-164
Commuting	0	0	0	0	0	0	0	0-30	0	0-30
<b>TOTAL</b>	<b>16-74</b>	<b>0-2860</b>	<b>107-319</b>	<b>42-136</b>	<b>12-280</b>	<b>59-302</b>	<b>36-144</b>	<b>72-289</b>	<b>120</b>	<b>464-4524</b>

FIGURE 4. Scenario for the rate of Danish energy use at the end-user in year 2030 (W per cap) (Sørensen, 1994).

	1. Cooling & refrigeration	2. Space heating	3. Process heat under 100°C	4. Process heat 100-500°C	5. Process heat over 500°C	6. Stationary mechanical energy	7. Electric appliances	8. Transportation work	9. Food energy	TOTAL
A. Biologically acceptable surroundings	0	258	0	0	0	0	0	0	0	258
B. Food and water	18	0	3	6	0	0	0	0	120	147
C. Security	0	1	0	0	0	0	0	1	0	2
D. Health	0	0	129	0	0	0	0	0	0	129
E. Relations, leisure	0	0	0	0	0	0	48	36	0	84
F. Activities:	0	0	0	0	0	60	0	9	0	69
Construction	12	120	12	0	0	6	24	27	0	201
Trade, service and distribution	0	0	12	0	0	6	0	3	0	21
Agriculture	9	102	12	12	6	60	24	9	0	234
Manufacturing industry	0	0	12	12	12	30	12	9	0	87
Raw Materials and energy industry	0	24	0	0	0	0	2	0	0	26
Education	0	0	0	0	0	0	0	9	0	9
Commuting	0	0	0	0	0	0	0	0	0	0
TOTAL	39	505	180	30	18	162	110	103	120	1267

Figure 5. Scenario for Danish biomass sector anno 2030 (indirect energy inputs through chemical fertilizers etc. are not included).  
Units: PJ per year.

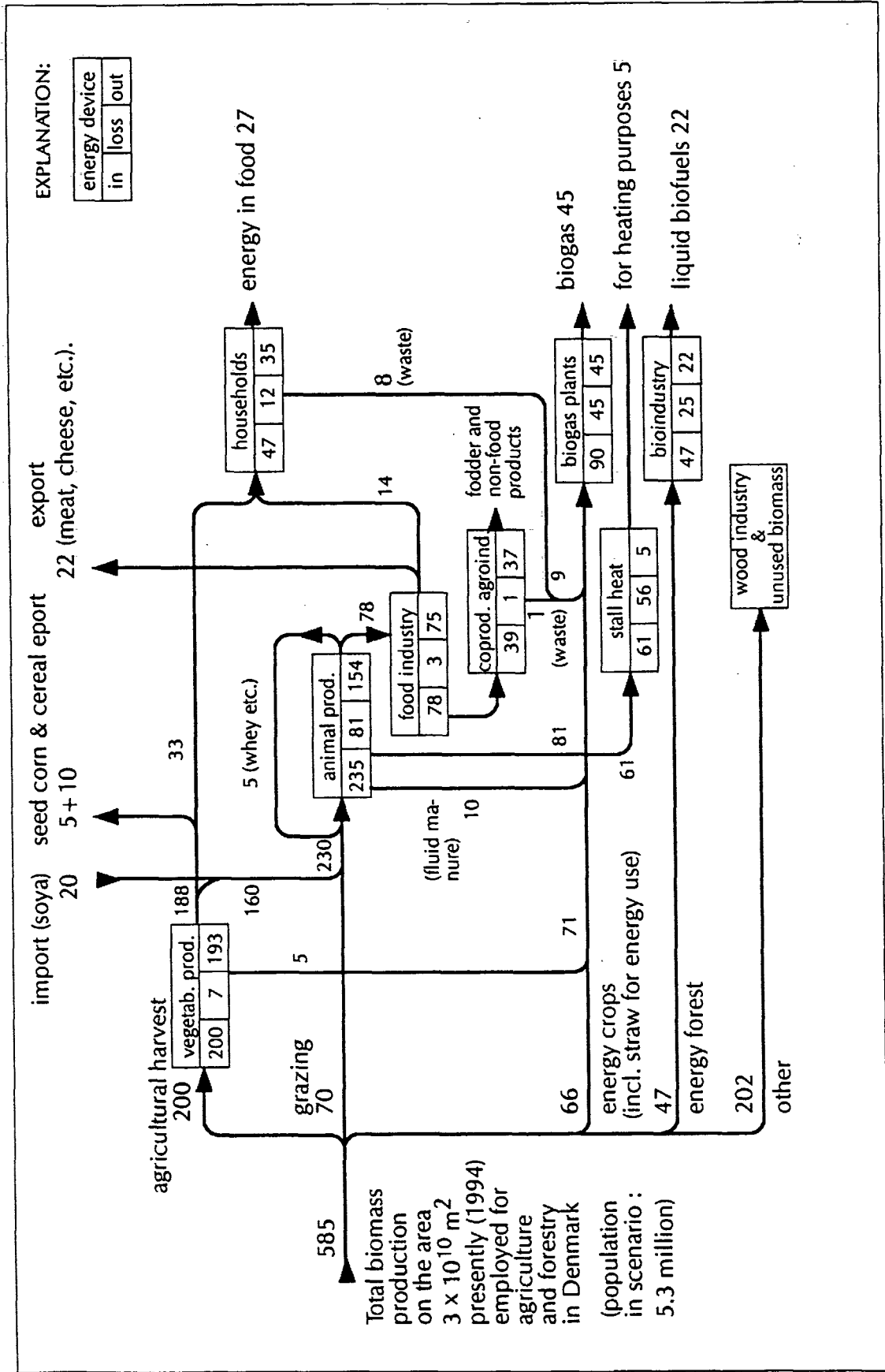
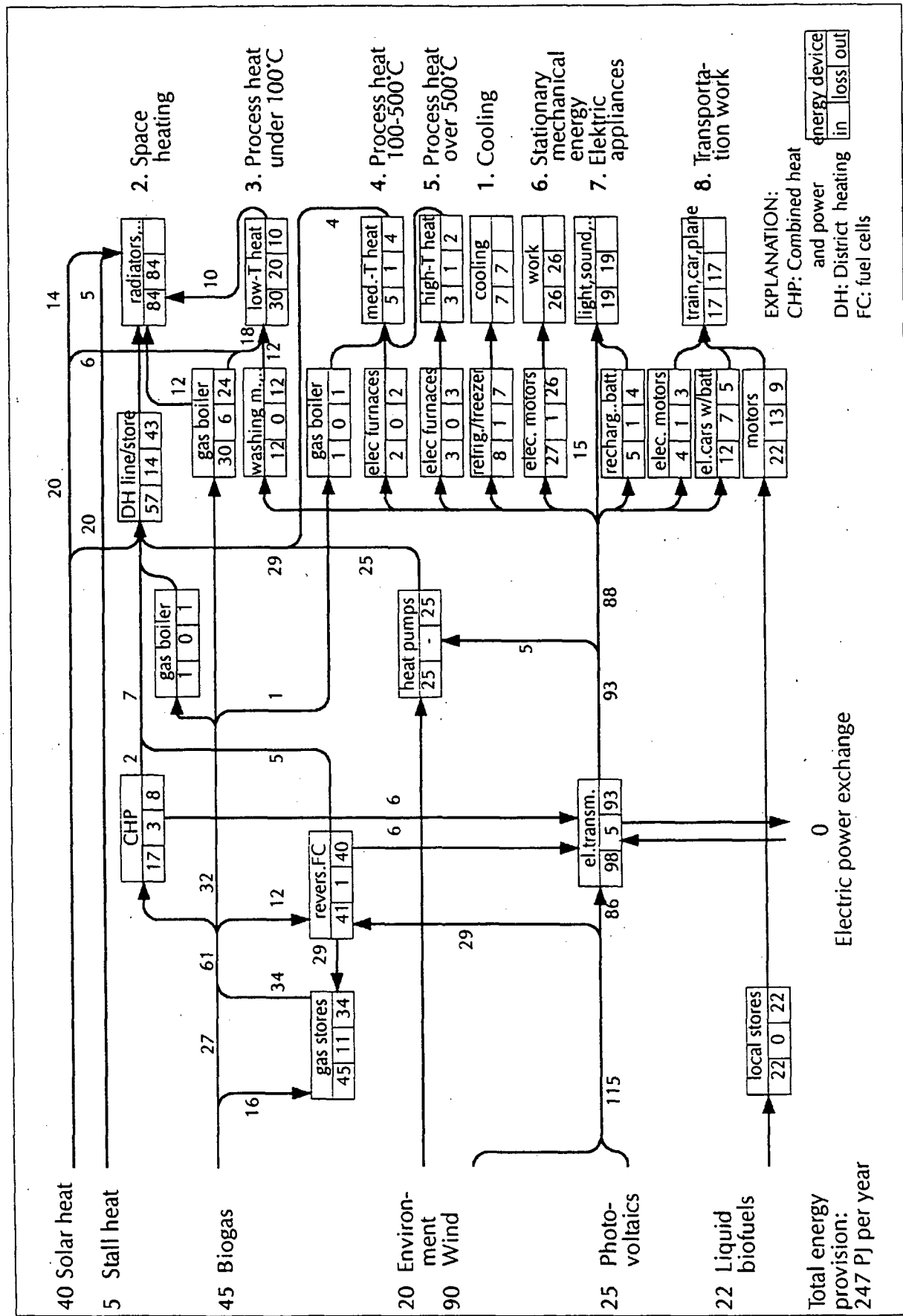
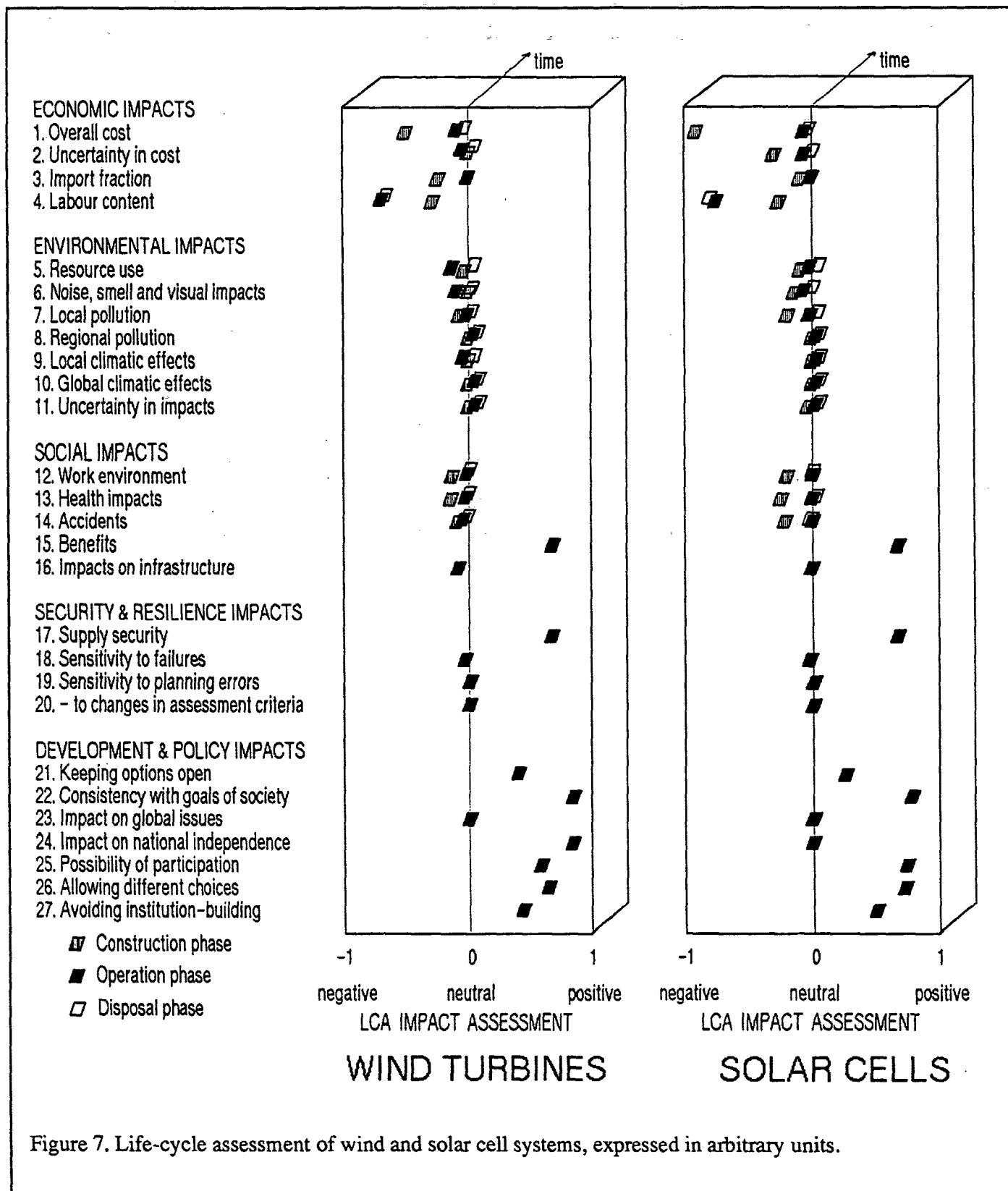




Figure 6. Scenario for a renewable energy based system for Denmark anno 2030 (units: PJ per year). (Sørensen et al., 1994)





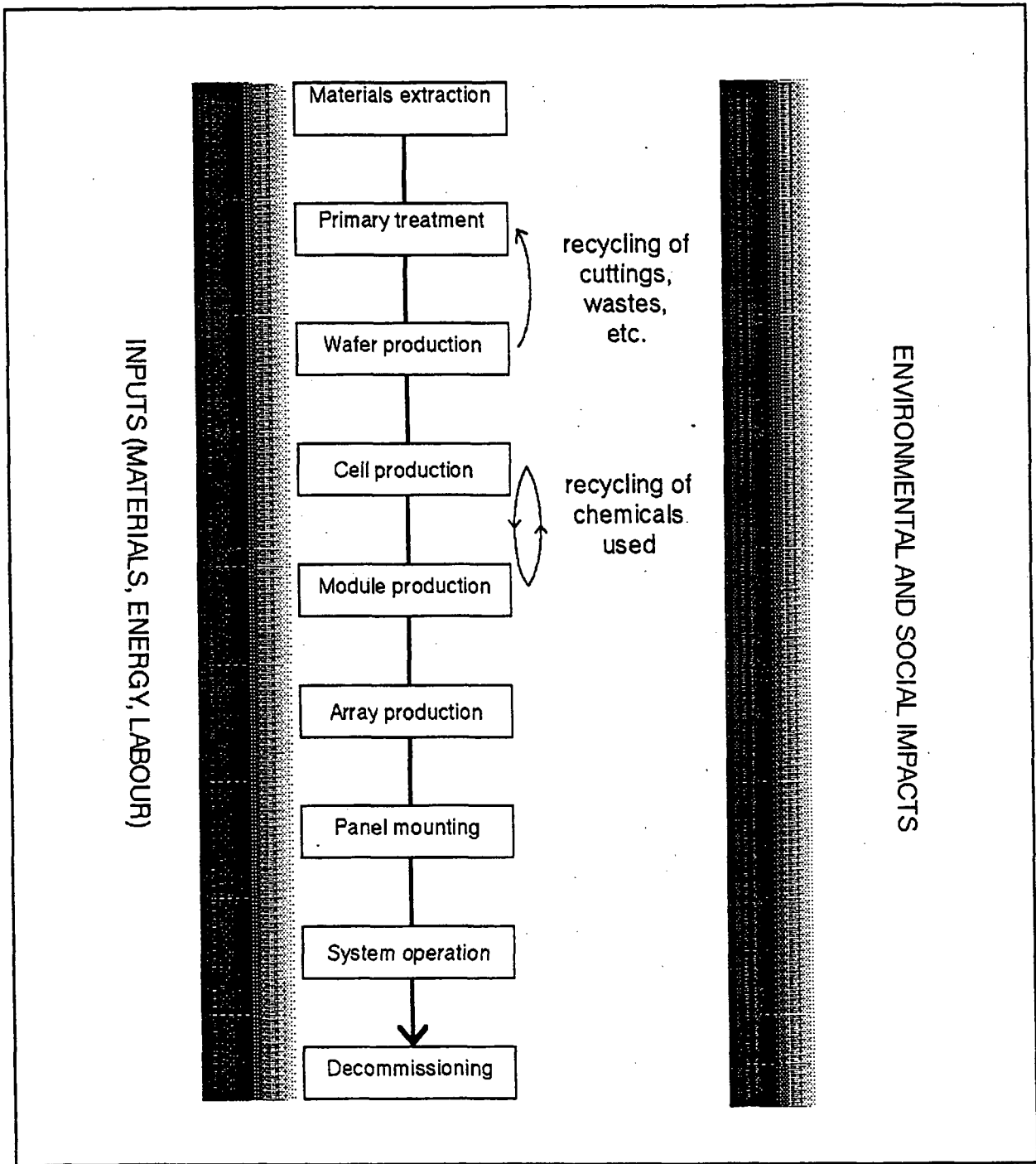


Figure 8. Main steps in PV life-cycle.

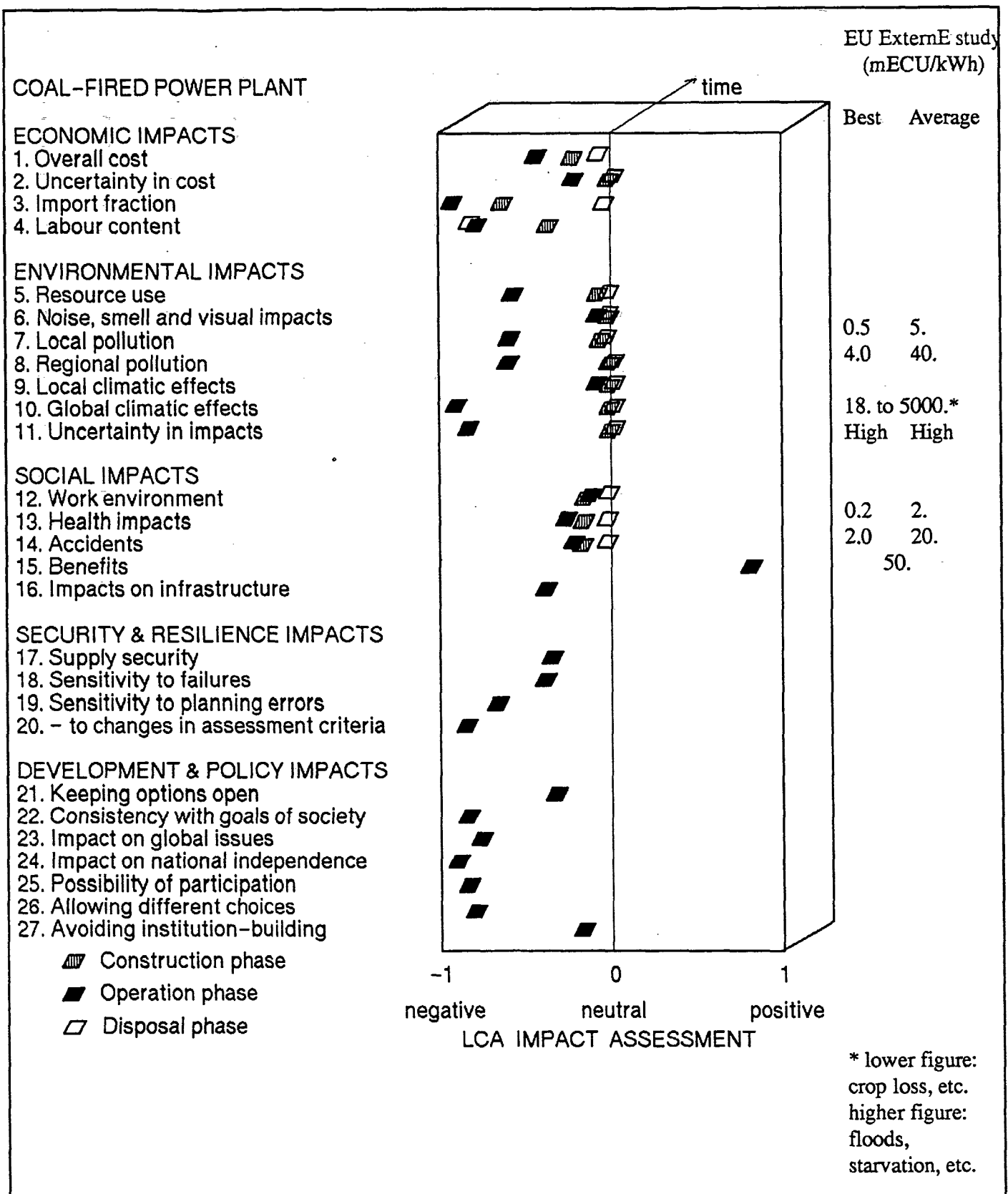


Figure 9. Life-cycle impacts of coal power life-cycle.

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