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RENEWABLE ENERGY AND ENERGY STORAGE

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Summary

This paper deals with methods of describing and assessing energy storage systems. The emphasis is on combinations of renewable energy sources and storage facilities, that can form systems of dependable energy supply. After a discussion of traditional energy systems and their use of energy storage, a number of system combinations are surveyed, which may serve various purposes in future energy systems, based on renewable energy sources or on new types of fuel. The applications range from very specialized ones to total regional energy supply systems. Examples of regional total energy systems are given, including a discussion of the time variations in the energy contents of energy storage components of the system.

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1 Energy storage strategies

Traditionally, energy has been stored in the form of wood, coal, oil etc. in order to be able to follow variations in demand and in order to achieve supply security. Thus, storage has been taking place before energy conversion, or at least before the main energy conversion step. Initial conversion steps, e.g. conversion of wood into charcoal, have in some cases been performed in order to obtain a more convenient form of stored energy. Refining crude oil to a number of products suited for different uses is also in this category. The example A in Fig. 1 offers an illustration of the conventional scheme for fuel resources.

Some of the renewable energy resources are also characterized by the presence of a reservoir containing energy in such a way that the scheme of usage will typically be similar to that of fossil fuels. Examples are biological material storage (straw, wood) and elevated water storage (for use in hydro power plants). Other renewable resources are based on energy flows (solar radiation, wind, etc.) that have to be converted before use or before storage in a convenient energy form. These sources are also characterized by variable input with time, so that direct conversion to cover a given demand may only be feasible at certain moments. If such sources are to cover demand at any time, a storage component must be part of the system. This may either be energy stored after the initial conversion, at times where renewable energy input exceeds demand (example B in Fig. 1), or it may be a fuel energy system operated as back-up for the renewable energy system. The fuel may be a synthetic fuel derived from a renewable energy source by a primary conversion step (methanol from biomass, hydrogen from wind or solar power, etc), in which case the usage chain illustrated in Fig. 1 C is realized.

Finally, it should be mentioned, that storage after conversion is sometimes used also in connection with fuel resources. This is the case, if the capital cost of the conversion equipment is high and the load fluctuating. Then the conversion unit may be operated continuously, and surplus production may be stored. In this way the conversion equipment may have a smaller rated power level than the peak load, since the excess load may be covered from the energy store. This scheme of storage operation, illustrated in Fig. 1 D, is called peak shaving.

Quite generally, the incorporation of one or more energy storage facilities in an energy supply system may be called for due to time variations in the energy source input, in the demand on the load side, or both, and it may be required by economic considerations depending on the relative cost of various system components, independent of whether there is a physical need for storing energy or not.

It would in most cases be more important to consider energy storage if the system comprises renewable energy sources of the flow type, and if such sources constitute large fractions of the supply system, energy storage will be a necessity if the system is required to satisfy load at any time, i.e. if the loss of load probability should be as low as that of current fuel-bases energy supply systems in the industrialized regions of the world.

2 Characteristics of energy storage facilities

An energy storage facility may be schematically represented as shown in Fig. 2. It accepts a certain form of energy, usually stores the energy in a different form and is capable of delivering energy in a third form, eventually identical the input energy form. Thus, an energy conversion process will typically be required at the entrance to the energy storage unit, and another one at the exit. Both are characterized by a conversion efficiency, say η_{in} and η_{out}, so that the "storage equation" describing the energy content W of the storage may be written

$$\frac{dW}{dt} = \eta_{in}E_{in} - \eta_{out}^{-1}E_{out} - E_{loss}. \qquad (1)$$

Here E_{in} and E_{out} are the energy fluxes into and out from the storage facility, and E_{loss} is the energy lost per unit time from the storage compartment, usually a function of time, eventually implicitly through a dependence on W.

Some storage systems involve more than one form of energy simultaneously, and generally, the input may be considered to consist of a number of parallel energy forms, each undergoing an initial conversion step to provide a (different) number of energy forms, some of which are stored and rest is lost or diverted to other applications. Similarly, the storage losses may be in various forms, some of which useful, and the exit conversion processes may each deliver a number of output energy forms, to be utilized for various applications or wasted.

As an example, consider a hydrogen storage facility attached to an electric power grid. The input conversion step may consist of electrolysis, performed with a separate device. In addition to the electric input, the elctrolysis unit may draw heat from the surroundings (cf. e.g. Ref. 1). The input conversion efficiency may be about 0.8. The next step is the storage of the hydrogen produced by electrolysis, say in steel containers or underground cavities. Energy input may be required for compression, and losses may arise for underground storage in case of leakage. Finally, electric power may be regenerated by burning hydrogen in a gas turbine, or by use of a fuel cell, assuming that the oxygen from the electrolysis were also stored. Typical conversion efficiencies for the output steps are in the range 0.4 to 0.6. However, some of the remaining energy may be in the form of useful heat, for which a credit may be accorded. If hydrogen can be used instead of electricity, the final conversion step may be omitted and the conversion loss avoided. For a situation where the hydrogen facility is considered only as a storage unit for the electricity grid system, the storage cycle has an overall efficiency of 0.3 to 0.5, the latter case demanding use of fuel cells and minimal or absent losses during storage of the separated hydrogen and oxygen.

In this example, the three components of Fig. 2 were physically separate entities. Other storage facilities combine two or all three components: Pumped hydro storage usually have two-way turbines serving both for pumping and for generating power, i.e. common input and output conversion unit but separate storage unit (the elevated reservoir). A similar situation exists for flywheel storage, while battery storage may combine all three functions.

3 Energy storage systems

An energy storage system is a setup aimed at supplying a definite energy supply service by means of certain conversion and energy storage units connected to each other and to the energy demand points (the load) by suitable transmission lines. Many energy storage systems are of the simple structure illustrated in Fig. 1B, but as mentioned in section 2, a need for systems comprising more than one storage unit may arise. Fig. 3 illustrates two concepts of multistorage systems. One aims at using several energy sources and converter types to satisfy a given type of load. This is called a hybrid system and its structure is indicated in Fig. 3A. Fig. 3B illustrates a "combined system" (cf. Ref. 2), in which a single energy source and conversion unit is used to satisfy a range of different load types. In both cases, a number of energy storage units is used to handle the different energy forms.

Examples of hybrid systems are found in vehicles with electrically charged batteries plus a short-term storage unit, e.g. a flywheel or a compressed air system, to satisfy peak power demand (during start and acceleration) and to recuperate some of the deceleration energy. Such systems are of particular interest in connection with battery types limited to modest discharge rates. Other vehicle hybrid systems may consist of fuel-based conversion systems combined with a peak-shaving storage facility, or may consist of a primary storage system (e.g. electrically charged batteries) plus an emergency fuel-based back-up system.

One example of a combined system would be a biomass conversion system having as output both liquid and gaseous bio-fuels as well as waste heat. The gaseous output ("biogas") may be used to produce electricity in a gas turbine, and the co-produced heat may be fed into district heating lines along with the possible heat surplus from the biomass digestion process. When demand for electricity is below potential production, the alternative route of using the biomass for a fermantation process yielding a liquid fuel (such as ethanol) may be applied, and the ethanol may be stored for automotive use or later conversion into electricity and heat.

4 Survey of applications

Application areas for energy storage systems include utility systems, transport, industry and building comfort, as well as basic energy supply in isolated regions and other situations calling for a high degree of autonomy.

A utility system is characterized by the presence of a transmission network, and for an electric grid, the power produced by conversion from various energy sources would be introduced into the grid at various locations (often a limited number), while loads are attached to the same grid, usually as a large number of independent connections. The electricity production may take place by co-production of electric power and heat, if a heat distribution system is available, or if heat can made useful close to the power plants. Phase differences between electricity and heat demands can be taken care of by use of heat storage facilities, typically with a day to night storage capacity. Energy storage facilities capable of re-generating electrity may be introduced between the energy source conversion plants and the grid, or at any convenient point connected to the grid. As mentioned, such storage could serve to smoothen out variations in supply or in the rate of conversion (in the primary conversion plants, by peak-shaving operation of the storage system).

In the transport sector, storage systems may be stationary or portable. Stationary energy storage may be in the form of synthetic fuels (e.g. methanol or hydrogen produced from renewable energy sources), with small amounts being transferred to vehicles just as with currently used oil-based fuels. Portable storage systems may be rechargeable stationary units, which can be carried into vehicles, used and returned for recharging. An example would be electric batteries being charged from co-generating stationary converters (such as biogas-fuel turbines or diesel engines) or from purely electric generators (e.g. wind energy converters). Charging could take place in garages of buildings (which would utilize co-generated heat), either when the vehicle is not in use or in a scheme of two battery sets, one being in the vehicle and the other being re-charged, with exchanges at suitable intervals. Alternatively, a service net of charging stations could be imagined, which would sell re-charged battery sets to vehicle owners much in the same way as gasolin is traded, and would recycle discharged battery units. Other automotive battery operations would involve batteries permanently placed in the vehicles, for peak-shaving applications.

For industrial purposes, energy systems would typically be of the co-generating type, providing electric power as well as heat for processes at various temperatures. Optimum efficiency is obtained by a cascading system, in which "waste heat" is used several times at declining temperatures. The initial conversion into electric power or very high temperature heat is used e.g. by the metal industry. Its discarded heat energy may be recovered and either serving as input to a new temperature rising cycle or it may be utilized as medium temperature heat for other processes, in the same industry or in other industries, which then have to be located at reasonable distances from the high-temperature industry. The scheme may then be repeated, using waste heat from medium-temperature processes as new imput or as a basis for low-temperature processes (or space heating). Storage systems may play a very important role in the heat cascading applications, because the various processes would typically be time-displaced.

Finally, energy storage technologies may play a role for comfort systems in buildings. The comfort energy demands would often comprise cooling, refrigeration, space heating and hot water supply, the distribution on these demands being correlated to climatic conditions and building use. A general energy supply system would therefore include a cold storage as well as a hot storage. These may be based on heat capacity (water, rock, soil etc) or on chemical phase change energy (latent energy of melting, evaporation, hydration, structural change, etc.) or on the energy of (reversible) chemical reactions. Buildings with solar collectors on the roof would in high-latitude locations need a seasonal heat storage. Due to losses (even in case of heavy insulation), heat capacity storage systems are unsuitable except maybe for very large communal systems, and phase-change ("loss-free") storage types would be preferred. The heat from the solar-hot storage system may be used to drive absorption-type cooling and refrigeration systems, but as the heat excess may not be available at the times where the need for cooling or refrigeration exists, then the addition of a "cold storage" may highly improve the performance of the system.

Autonomous systems may combine aspects of all of the abovementioned application types, for instance on a smaller scale for rural applications in developing countries, or they may be part of a total energy system for a larger region with highly developed energy transmission facilities.

5 Total energy systems

A total energy system aims at satisfying all the energy-related needs of a region. The natural borders of such a system may not be that of countries or administrative sub-units, because of the uneven geographical distribution of components that may supplement each other in forming a total energy system of optimal stability and efficiency. Conditions for electricity production by wind energy may for example be present in one country, while hydro storage facilities for making the wind energy acceptable as a dependable system component may be available only in a neighbouring country. Similarly, the conditions for large-scale production of bio-fuels may exist in areas, where there is little demand for such fuels, while the same areas may be less suited for food crops, so that a stable system could be obtained by respective export and import of food and fuel. This kind of mutual dependency is well-known from trade in conventionel fuels, where - however - the dependence in some cases is highly unilateral due to extremely uneven distribution of resources. In a future situation, where most energy may be derived from renewable resources, all regions of the world will have a basic amount of potential energy sources. Yet, the differences in population density and the local mix of suitable renewable energy resources will make it necessary to consider energy systems on an enlarged regional basis, from which the most suitable combination of technologies may be employed (cf. chapter 6 in Ref. 1).

Fig. 4 illustrates an example of a total energy system, based on three types of distribution systems: an electricity grid, a district heating line network and a pipeline system for hydrogen transport (most presently designed natural gas transmission systems can be used for hydrogen without alteration). In addition, a portable energy system based on biofuels is indicated for use in the transportation sector. Alternative solutions would employ electric vehicles or hydrogen-fueled vehicles (e.g. based on hydrogen trapped in metal structures).

A mix of renewable sources of energy is assumed to form the basis for conversion. Wind and hydro converters produce only electricity, and the hydro plants serve as back-up for wind, eventually assisted by pumped storage facilities. Photo-voltaic converters produce electricity as well as heat (because waste heat is assumed to be led into a building heat distributing system or directly into district heating lines). The solar cells are placed on building rooftops or outside walls. Buffer heat storages serve as day to night heat displacers, while any electric oversupply is used to power electrolysis cells, probably in the form of large, industrial units. Hydrogen is used for industrial processes, and may be combined with oxygen in fuel cells, if the available hydro storage is insufficient to cover the electricity supply and demand fluctuations. Also the fuel cells are co-generating, feeding waste heat into the low temperature heat distribution system. Industrial process heat is cascaded to applications at declining temperatures, and finally reaches the temperature level of the district heating system. Solar heat-producing collectors may contribute to industrial heat supply (concentrating collectors), while any low temperature heat beyond what can be covered by waste heat would be produced by rooftop flat-plate solar collectors. As these are usually giving the largest contributions in the seasons with the least heat demand, seasonal heat storage facilities have been included. Finally, the system depicted in Fig. 4 considers the production of synthetic fuels from biomass residues (i.e. non-food parts of food crops, organic waste and eventually plants grown for energy purposes, but in symbiosis with food production - such as interim nitrogen-fixing crops). If such fuels are gaseous (biogas digester output) they could conceivably be refined to pipeline quality, but it is more likely that liquid fuels obtained by fermentation of the biomass residues (or alternatively by gasification of wood followed by catalytic synthesis) will be more versatile. Specifically, these fuels could serve the transportation sector, which would otherwise require a complete re-structuring relative to the present situation, in order to accept all-electric or hydrogen-based propulsion.

The emphasis on various components of a renewable energy system of the type just described may vary according to climatic conditions (Ref. 1) and to load structure. It would be possible to construct a number of other total energy systems, based on different expectations to future choices of energy sources. Alternatives to renewable resources may be low-grade fossil fuels, or nuclear fuels combined with breeder or fusion technologies.

6 Performance models

In Figs. 5 and 6, two examples are given of concrete models based on the general total energy scheme developed in the preceding section. The models are in a form suited for numerical simulation calculation, but the examples are here only given to indicate the kind of time-matching problems, that may be addressed by such calculations. Therefore the illustrations only indicate the type of time variations expected on the load side, and a number of selected time variations of storage energy contents, which should be among the outputs of a simulation calculation.

Fig. 5 is an illustration of the Danish energy system as it looks today or rather in a few years, when the ongoing natural gas project will be operative. Denmark will then be served by a common natural gas pipeline system, two separate electricity grid systems and considerable number of district heating systems, covering those densely populated areas with reasonable access to co-generating power stations. Coal, oil and natural gas is shipped or piped into the central storage facilities indicated on the right hand side of Fig. 5, following treatment at refineries, or is being fed directly into the distribution system, as in the gas case. Through local storage and conversion units, the energy is transferred to the distribution systems or is transported to the customers. The different load types are illustrated on the left hand side of the Figure.

The rectangular inserts indicate the time variation, either for a diurnal cycle (a scale of 0 to 24 hours) or on an annual cycle (a scale of months, from J=January to D=December). For electricity and heat loads two diurnal cycles are indicated, the upper one being for a winter day, the lower one for a summer day. All inserts give relative time variation in energy content of energy storage facilities, based on estimates. The absolute amounts of centrally stored fuels are in the range from 3-6 months of average usage, while those of local storages are smaller, except for local oil storage at the individual household fossil boilers. Gasolin stored in individual vehicles is usually the equivalent of about one week of average usage. The storage associated with fossil power plants used to be determined by total winter requirements, which would have to be present at each power station before the time of year, when frost could become severe enough to freeze the waters giving access to coal-carrying vessels. For some years, the availability of ice-breaking ships allowed a relaxation of this requirement, but at present the amounts of stored fuels are again being increased in order to lessen the impact of sudden supply disruptions.

Several of the Danish power plants are co-generating heat for district heating lines. In 1978, the heat output was 40% of the electric output (Ref. 3). One co-generating plant has a two hour heat storage, that accumulates heat during electric peak demand conditions, for use the following night, when electricity demand is small but heating required, during winter. The total waste heat from all power stations is 2-3 times that utilized. Apart from geographical considerations, the heat that could become useful for heat applications is limited by the high temperatures (90-110°C) chosen for the Danish district heating lines.

On the top of Fig. 5, the electric energy exchange with neighbouring countries is displayed. The seasonal trends in each direction, which are indicated in the boxes, are for 1978 (Ref. 4). Historically, the annual net values have shifted between positive and negative values, depending on water conditions in the Scandinavian hydro reservoirs and on the discrete changes in installed power for the countries involved (Sweden, Norway, Federal Republic of Germany). For the mid-1980'ies, a large power surplus will be present in Sweden, so that a net Danish import may be expected.

The relative share of the load sectors were in 1978 as follows: Electricity 13%, heat 33%, industry 25% and transportation 29%. During the late 1970'ies, the trends in heat use has been downwards, that in industrial use upwards and the two other ones about unchanged (Ref. 5).

A quite different energy system is depicted in Fig. 6. This is a future Danish supply system based entirely on renewable energy sources, the result of a 50 year transition described in Ref. 6. The electricity supply is based on wind turbines combined with the hydro installations of the other Scandinavian countries, assuming reinforcement of the interconnecting sea cables. The performance of the electricity producing trends and the variations in energy content of the elevated water reservoirs have been taken. The two limiting curves represent extremes of combinations of non-average wind and percipitation patterns. The influence of the wind variability is much less than the influence of the hydro variability. In this scenario, electricity is also used to power the industrial requirements for mechanical and process heat energy, due to the abundance of electricity-suited renewable energy sources in Scandinavia.

The low-temperature heating load is covered by solar collectors, either directly from rooftops to distribution systems with storage in the building, or through the district heating lines. The latter may be of advantage in densely populated areas, because the storage facilities would have an economy of scale, whereas the collectors would probabley still be on rooftops in order to avoid separate area demands. Local heat storage facilities would have to be of the phase-change type ("loss-free") in order to serve as seasonal storages in a solar system with no other back-up system.

Energy for transportation is to be provided from synthetic fuels, produced from biomass. Part of this may derive from the Danish agricultural sector, but part could also be based on wood, gasified and converted into methanol (Ref. 8), probably at central plants situated close to the forest resources (e.g. in Sweden).

This example of an energy system for use in some future is a good example of the application of simulation models, since energy planning is based on precisely the type of answers that such a model may furnish: How much energy storage is needed to obtain a stable system, and what should be the characteristics of each storage type. How much energy transmission capacity is needed, and how many converters for the different sources. The next step in the planning effort would then be to device a path from the present system to the one found desirable for the future. The Danish example, for instance, places some doubt on the natural gas distribution system, which may well become obsolete in a future energy system. Still, as hydrogen could be taking the place of biofuels, the main pipeline system may become useful. However, the wisdom of establishing a fine mesh of natural gas lines to individual households would seem more doubtful.

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Figure legends

Fig. 1. Energy conversion and storage strategies. This and the following Figures are from Ref. 9.

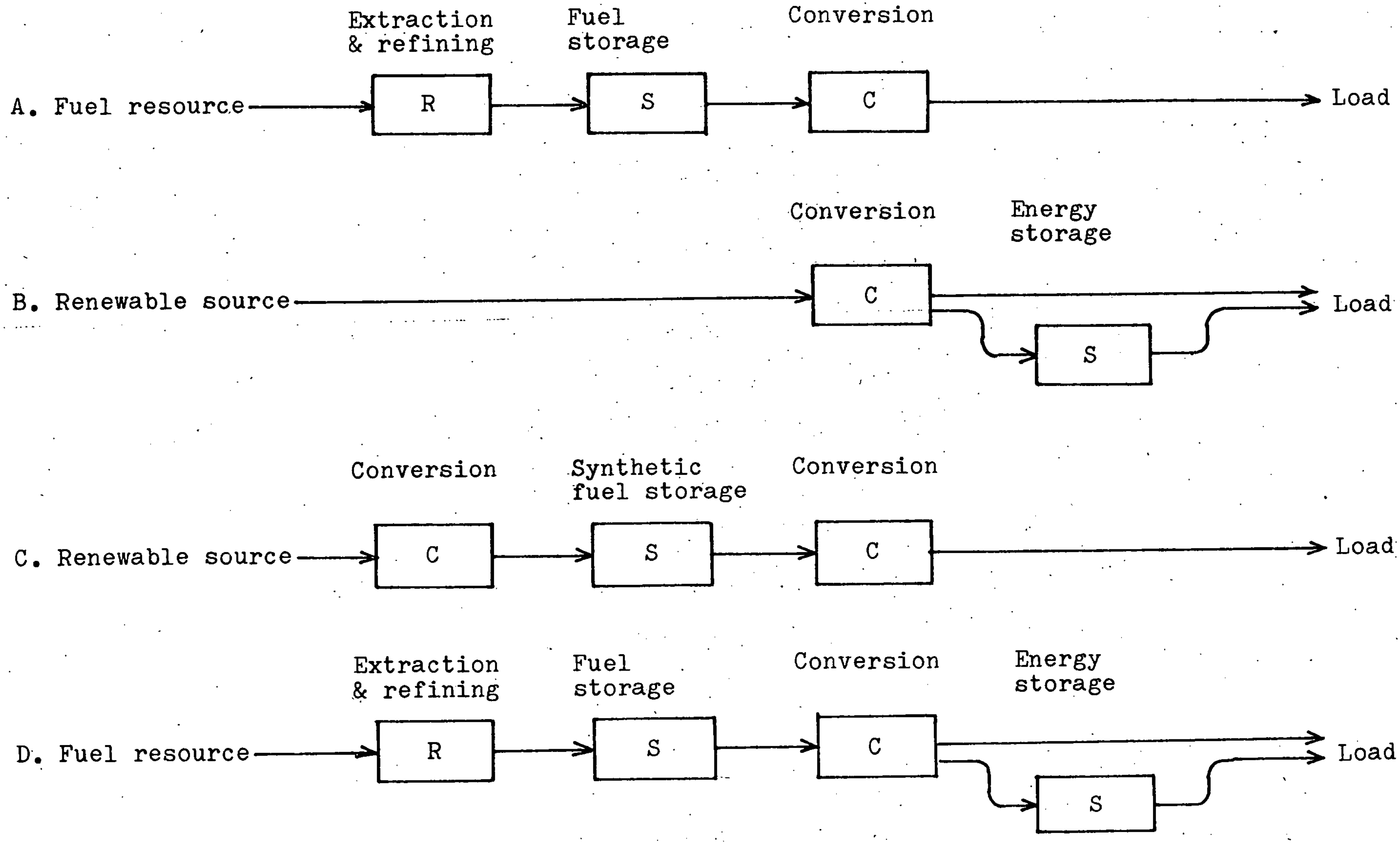
Fig. 2. Structure of storage system.

Fig. 3. Layout of hybrid and combined energy systems.

Fig. 4. Example of a total energy system. Dashed lines indicate heat transfer, and "BHS" stands for "Buffer heat storage", "envir." for "environmental".

Fig. 5. Danish energy system around 1985, indicating (in boxes) the relative variation in storage contents, loads and power imports and exports, on a diurnal (0-24 hours) or annual (January-December, J-D) scale. Heat transfers are indicated by dashed lines and "BHS" stands for "Buffer heat storage".

Fig. 6. Possible Danish energy system around 2025, cf. caption to Fig. 5.


Extraction & refining
Fuel storage
Conversion
A. Fuel resource
R
S
C
Load
Conversion
Energy storage
B. Renewable source
C
S
Load
Conversion
Synthetic fuel storage
Conversion
C. Renewable source
C
S
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Load
Extraction & refining
Fuel storage
Conversion
Energy storage
D. Fuel resource
R
S
C
S
Load

Fig. 1

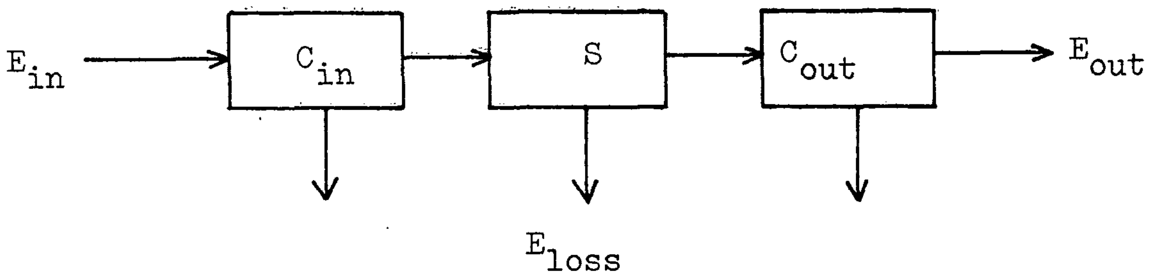
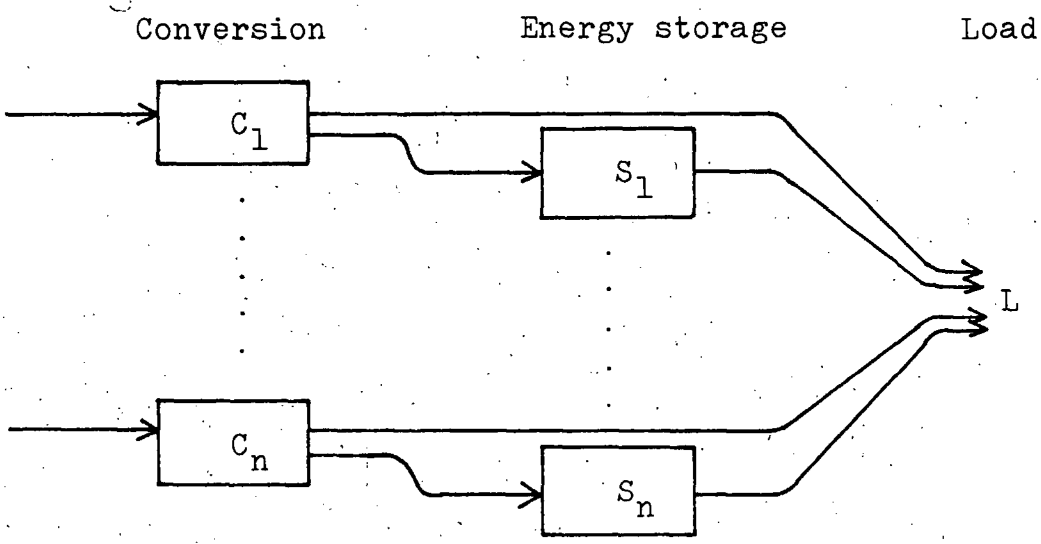
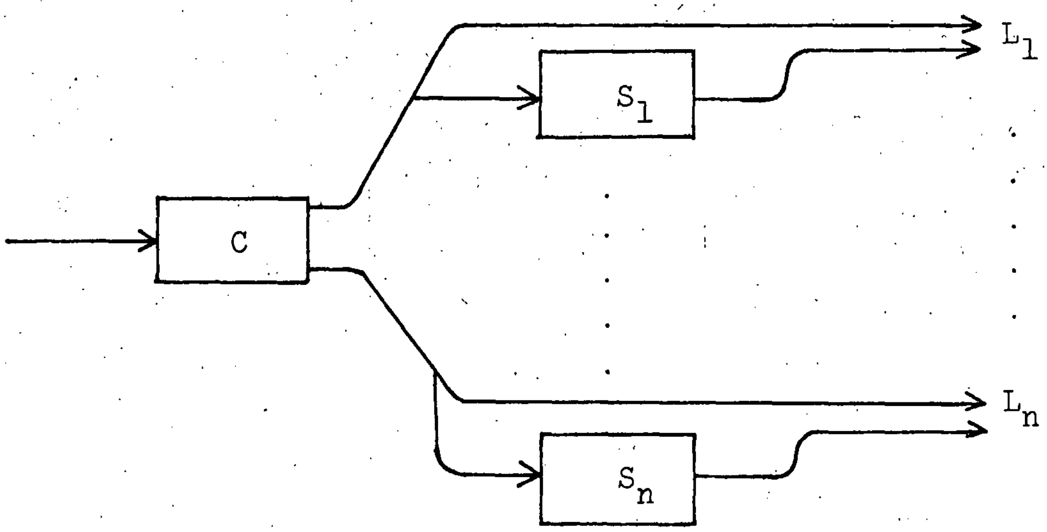


Fig. 2



A. Hybrid system



B. Combined system

Fig. 3

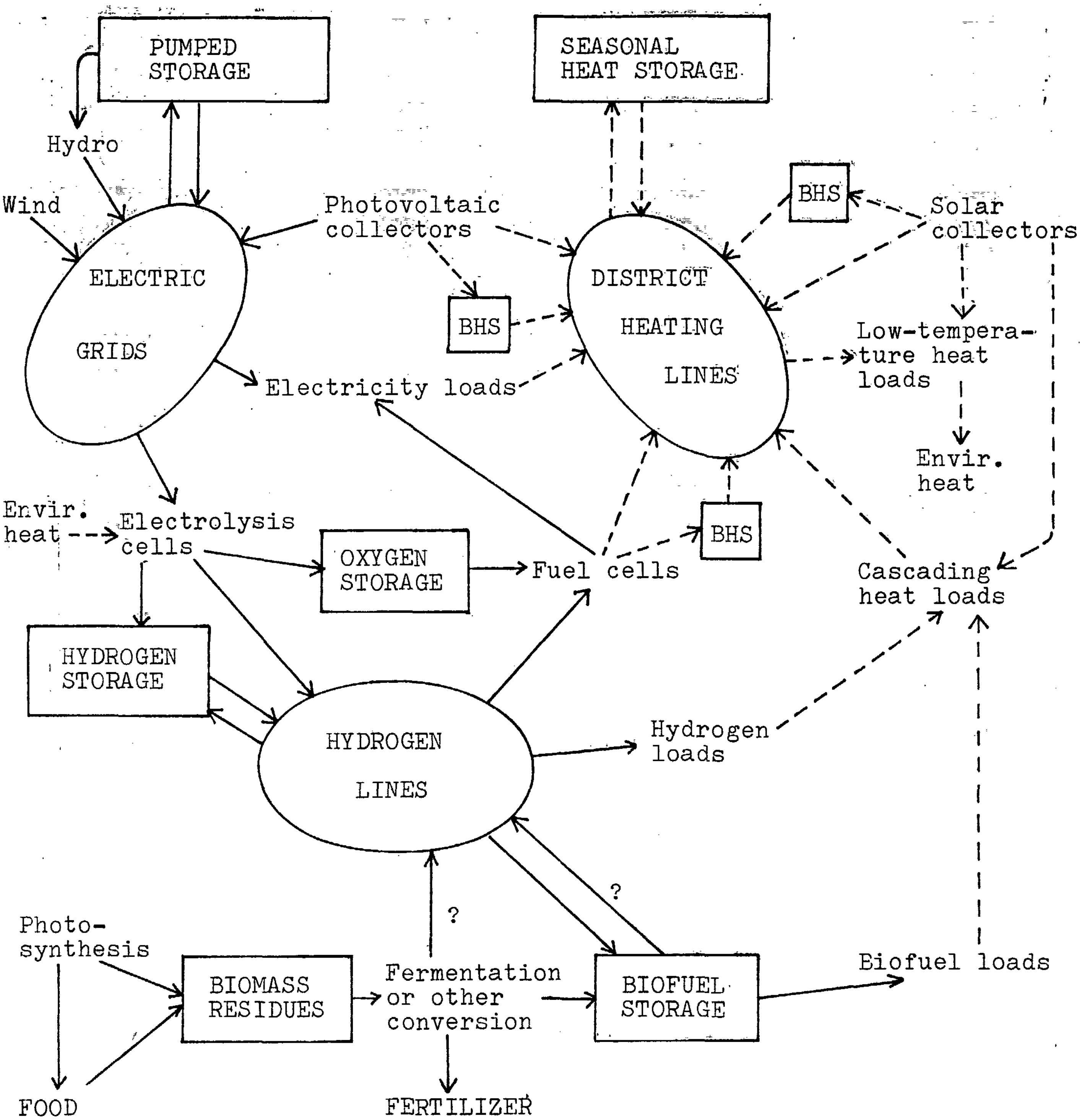

PUMPED STORAGE
SEASONAL HEAT STORAGE
Hydro
Wind
Photovoltaic collectors
BHS
Solar collectors
ELECTRIC GRIDS
DISTRICT HEATING LINES
BHS
Low-temperature heat loads
Electricity loads
Envir. heat
Envir. heat
Electrolysis cells
OXYGEN STORAGE
Fuel cells
BHS
Cascading heat loads
HYDROGEN STORAGE
HYDROGEN LINES
Hydrogen loads
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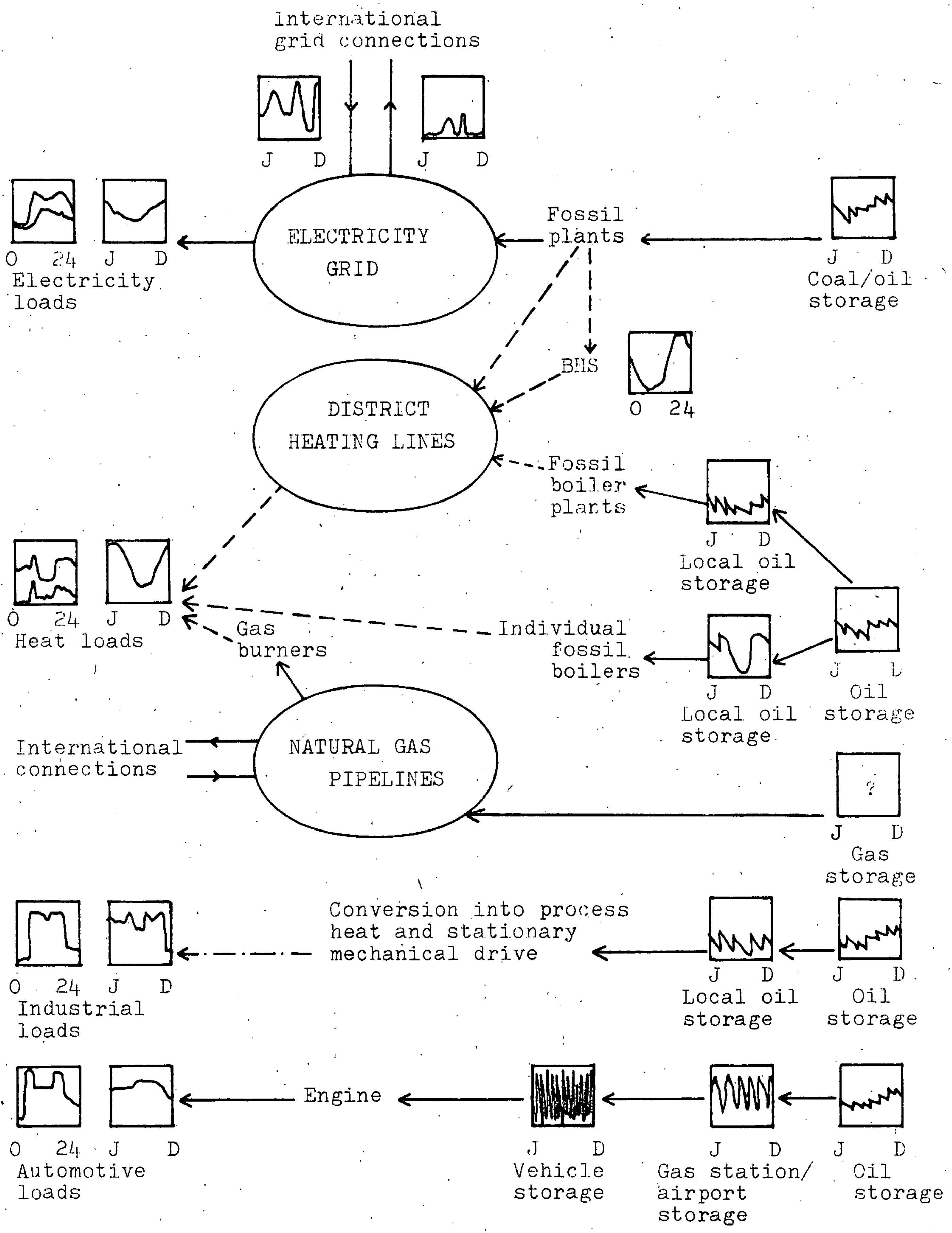
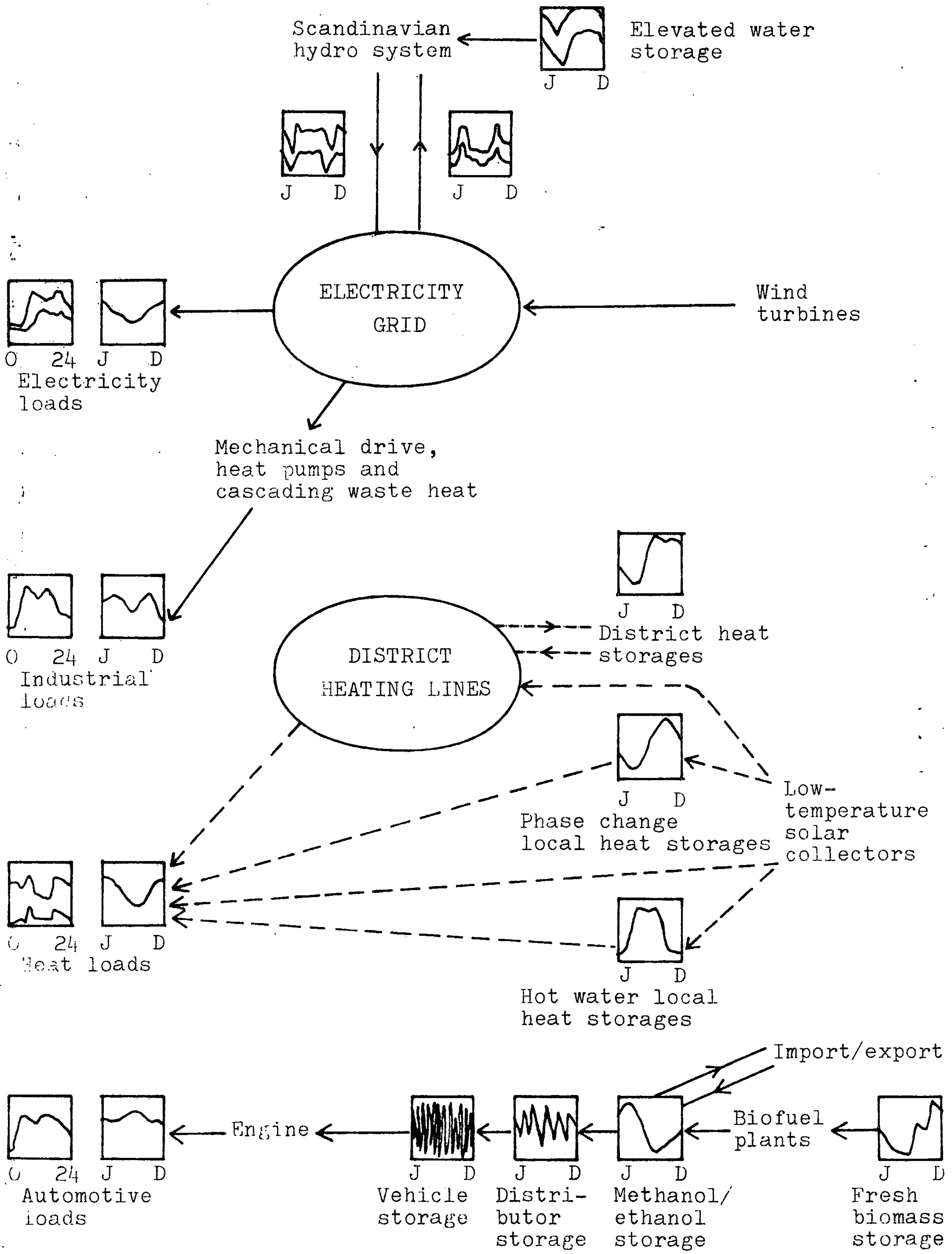
Photo-synthesis
BIOMASS RESIDUES
Fermentation or other conversion
BIOFUEL STORAGE
Biofuel loads
FOOD
FERTILIZER

Fig. 4



DANISH ENERGY SYSTEM AROUND 1985

Fig. 5



POSSIBLE DANISH ENERGY SYSTEM AROUND 2025

Fig. 6

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