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Storage and Transmission of Secondary Energy

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ABSTRACT

In the area of the total energy flow, possibilities and limits of shifts in time (storage) and in space (transfer) of secondary energy, i.e. electrical, chemical and thermal energy are examined and formulated. These shifts are linked to the qualitative conversions of secondary energy. The multiple technological possibilities, the spectrum of governing factors and the numerous technical and economical parameters show that only a complex optimization is possible.

1. INTRODUCTION

A simplified representation of energy flow in civilization is shown in Fig. 1. Unfortunately, nature's supplies are not adapted to the demands of producers and users. The differences can be divided into three groups:

- differences in quality and form between primary, secondary and useful energy,
- time lag between supply and demand,
- differences in geographical distribution: distance between sources, producers and users.

Table 1 shortly illustrates these problems. The purpose of this report is to point out possible methods of compensating the discrepancies between nature's supplies and producers' and consumers' requirements.

2. NATURE'S ENERGY CARRIERS

Nature gives mankind free energy in different forms and qualities as well as at different times. These primary energy forms can be discussed as follows:

1. Nuclear energy has two energy carriers: atomic nuclei of the light elements and atomic nuclei of the very heavy elements. To the first group belongs particularly an isotope of hydrogen, deuterium, and the artificially produced hydrogen isotope tritium. Deuterium is probably a gift from the time of the Big Bang, i.e., of the creation of the Universe about 15 billion years ago. Its high stability, i.e. very long lifetime permits enormous quantities of energy of approx. 100 000 GJ/kg to be transmitted and stored very efficiently right up to present time.

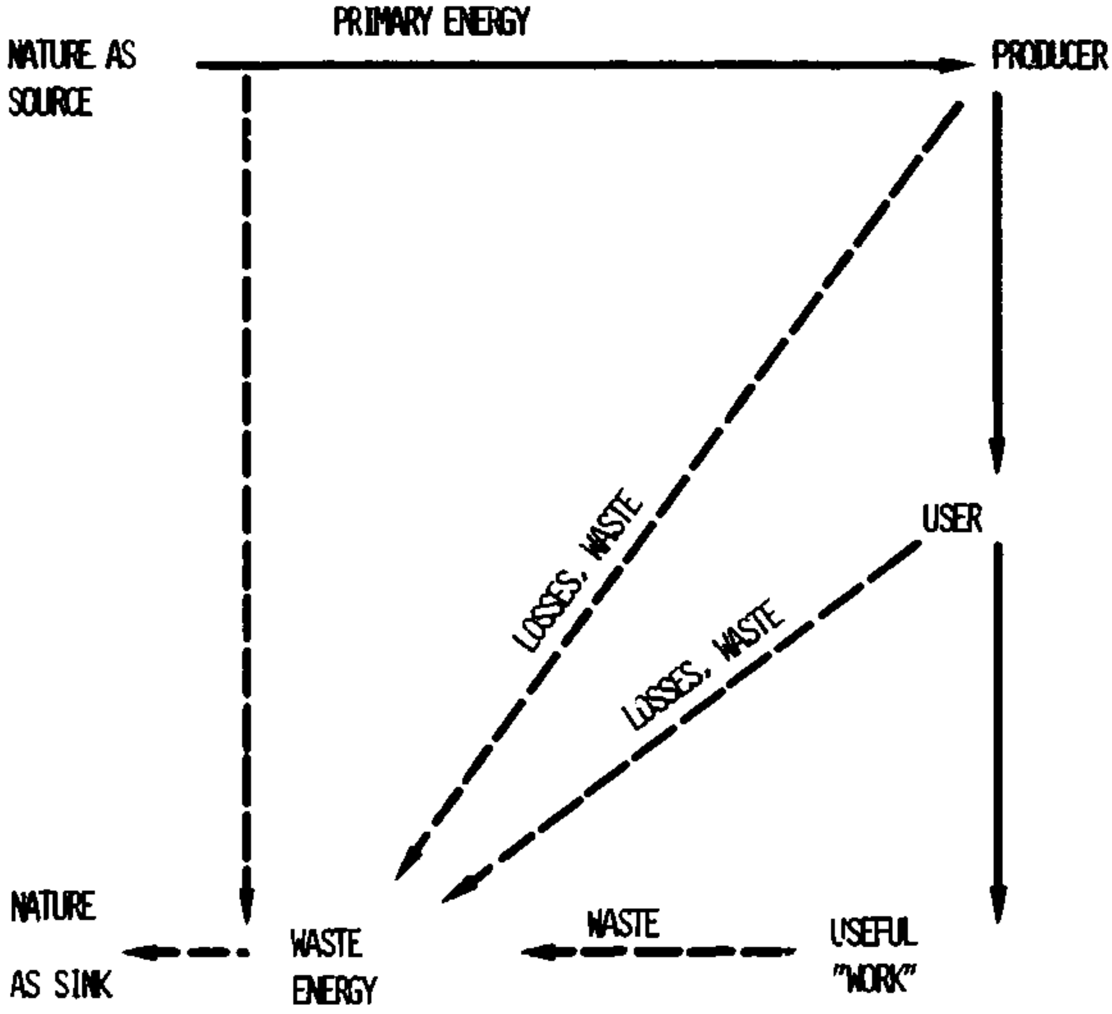

Fig. 1. Energy flow diagram

Characteristics of the Energy Supply and the Energy Demand

	Nature's supplies primary energy		Discrepancy between primary and secondary energy	Producer's needs secondary energy	Discrepancy between secondary and useful energy	User's needs useful energy
Energy distribution time in the	energy flow mostly not continuous: solar wind tides	stored: coal oil gas wood uranium		continuous and regular production, no fluctuations, if so, only on advance order		quantity and time at wish, fluctuations at wish, no advance orders on request
Energy distribution in the space	very irregular according to: - regions - climate, elevation - in water, air or in earth			central in one station, as close as possible to user evenly distributed		decentralized, far from "dirty" producer, unevenly distributed
Forms and quality of energy	very different kinds: - ga eous - liquid - solid	- nuclear - electro- magnetic - weak - gravitation		few and standarized forms		many different forms, but ex- clusively electro- magnetic energy and simple converters

To the heavy carriers of nuclear energy belongs the atomic nucleus uf uranium, in a larger sense also thorium. Both represent the gift of the explosion of a big star, a socalled supernova. Probably, uranium and thorium were supplied to us by two successively exploding supernovae at a distance of about 60 ligth years some 4.7 billion years ago. Though these elements are not very stable, their lifetime lies in the billion years range. Thus these energy carriers have very effectiverly stored the energy released by the supernovae up to our time and transmitted it to the Earth's crust. Their energy density reaches approx. 50 000 GJ/kg.

2. Electromagnetic energy is delivered to us in the form of sunlight (photons). For approx. 4.5 billion years nuclear energy processes have occured in the centre of the Sun, producing an enormous flux of solar energy.
   About 300 million years ago a big part of this solar energy on Earth was transformed into long-life energy reserves, stored and transmitted into various geological formations: mineral oil, coal and natural gas. All these carriers of chemical, i.e. electromagnetic energy contain approx. 0.04 GJ/kg.
   This same solar energy also significant shortlived quantities of stored chemical energy: wood and other products of the biosphere. The energy content corresponds to 0.01 GJ/kg, allowing only limited storage and transmission of this form of energy.
   The biggest and most important form of free energy on our planet was, is and will always be,the Sun. The massless photons, as a form of electromagnetic energy, transfer the energy of the nuclear processes in the centre of the Sun to us. The average value of this solar energy corresponds to approx. 5 GJ/m^2 per year. This form of energy is not directly storable and practically not transportable.

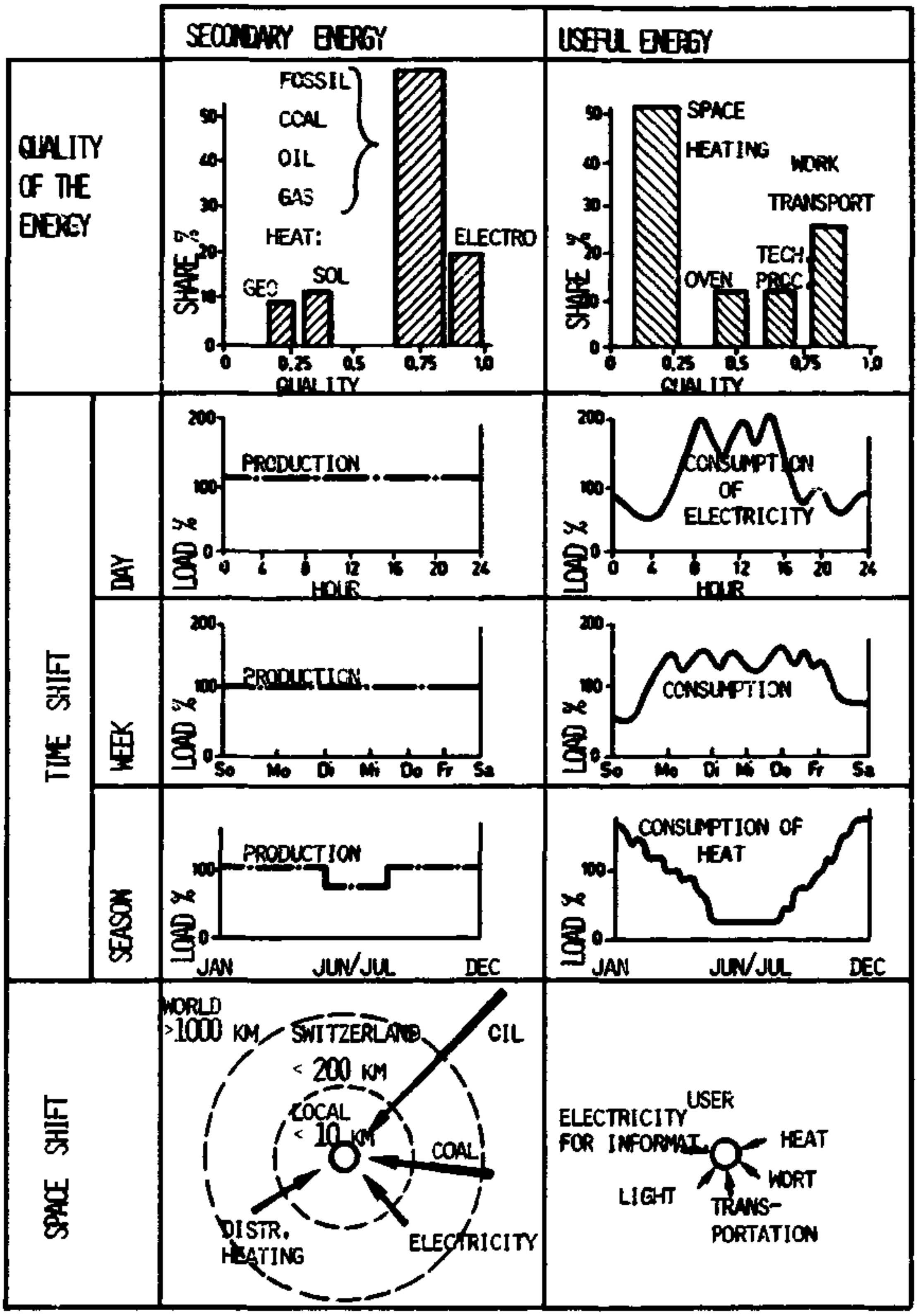

Fig. 2. Comparison of the Properties of Secondary and Useful Energy

This is certain that, besides the main problem i.e. transformation of the solar energy flow into other forms of useful energy, solving the problems of storability and transportability is of utmost importance to civilization. Without man intervening, the solar energy is transformed on Earth into various forms of mechanical energy: winds, waves and hydroenergy. Only the last form of solar energy is spontaneously stored in the atmosphere. Its energy content is approx. 10^{-6} GJ/kg.

3. The so-called weak nuclear energy can be observed in the radioactive disintegration processes of unstable atomic nulei. On Earth this energy form is responsible for the geothermal energy as a consequence of slow radioactive disintegration of potassium, thorium and uranium. The geothermal heat is distributed over the whole Earth's crust and corresponds to an energy density of approx. 0.001 GJ/kg. It is very well stored by nature itself. Unfortunately its transmission capacity is very low.

4. Access to the weakest of all elementary forces, gravitation, as a free form of energy is only possible in the form of the tides. This form of energy is of low intensity and is not storable. Its transmission capacity is very low.
   Table II gives a comparison of the elementary forms of energy which are of practical interest on Earth.

3. FORMS OF ENERGY EXPLOITED BY MAN

Naturally the form of energy which was and remains most important for man is the chemical energy contained in food. But man also needs other forms of energy the most important of which are listed hereafter:

1. Thermal energy as a substitute for the "lost Eden" with its subtropical climate: warm air and warm water. Man needs enormous quantities of energy to restore this subtropical microclimate.

Elementary Forces and Primary Energies (in brackets: Global energy flux in TW) (TW = 10^{12} W) Table II

		Elementary forces						
		nuclear	electromagnetic				weak nuclear	gravitation
			chemical	biological	light	thermal mechanical		
Specific energy content J/kg		$\sim 10^{13}$	$\sim 10^{7}$	$\sim 10^{7}$	$\sim 10^{8}$ kmol photons	$\sim 10^{5}$	$\sim 10^{12}$	$\sim 10^{3}$
Energy from nature	Energy flux			biosphere: algae, krill, trees, cane sugar.	sunlight (122000)	wind, water, ocean heat; geotherm. heat (32) ←	radioactive decay	tides (3)
Energy from nature: Stored energy	10 to 50 years ago		wood ←			—	—	—
	~1 million years ago		lignite ←	biosphere	sunlight	—	—	—
	300 million years ago		gas, oil, coal ←			—	—	—
	~5 billion years ago: supernovae	uranium, thorium				—	—	—
	15 billion years ago: Big Bang	deuterium				—	—	—

2. Thermal energy for the thermal treatment of food: cooking, frying etc.
3. Radiant energy, light to drive the darkness of the night out of his artificial caves.
4. Mechanical energy to economise an muscle force, and to amplify it.
5. Mechanical energy to economise his motive force and to significantly increase speed.
6. Electrical energy for operating his instruments in the information sector.

All these forms of energy, which man utilizes directly, belong to the electromagnetic energy. They are compiled in table III, with the exception of food.
The difference in quality between primary energy, delivered by nature, and energy usable by man is obvious. But there are other significant differences between primary and useful energy.

4. DIFFERENCES IN TIME AND SPACE BETWEEN PRIMARY, SECONDARY AND USEFUL ENERGY

Primary energy is found scattered in nature, often far from the potential consumer of usable energy, moreover at a time which does not correspond to the momentary energy consumption and in a form and quality which do not meet the requirements of the consumer. Fig. 2 shows in a very simplified form the three principal differences between secondary and useful energy: differences in quality; shifts in time and space.
Table IV tries to present in a simple way the problem of time and space shifts between the different kinds of energy. From this table one can see that useful energy, if at all, can only be stored and transferred with great difficulty. These functions have to be met by secondary energy. The important task to put secondary energy at the consumer's disposal at the right time and at the right place is the art of energy storage and energy transfer.

Possibilities of Transformation of Secondary Energy into Useful Energy

		Secondary energy (effective energy)						
		nuclear	electromagnetic				weak nuclear	gravitation
			electrical	chemical	light	thermal		
Useful energy only in the form of electromagnetic force	information sector	—	feeding	—	—	—	—	—
	work stationary		electro-engine	combustion engine stationary	—	—	—	—
	work means of transport	—	accumulator	combustion engine	—	—	—	—
	light		bulb	oil and gas lamp	—	—	—	—
	heat, high temperature	—	electric furnace (oven)	oil and	solar furnace			
	heat, medium temperature	—	electric heating	oil and gas heating	—	district heating	—	—
	heat, low temperature	—	electric heating	oil and gas heating	solar collectors	—	—	—
	cooling	—	mechan. refrigerator	oil, gas absorption install.	—	—	—	—

Suitability of the Various Energy Forms for Time and Space Shifts — Table IV

Primary energy		Time shift: storability			
		none	sufficient	good	very good
Shift in space, transportability	none	electromagnetic: sunlight	thermal: T<100°C (geothermal)	gravitation: tides	—
	suff.	—	—	—	chemical: solid (coal)
	good	—	chemical: gaseous (natural gas)	chemical: fluid (oil)	—
	very good	—	—	—	nuclear: deuterium thorium uranium

Secondary energy		Time shift: storability			
		none	sufficient	good	very good
Shift in space	none	—	latent thermal	thermo-chemical	—
	suff.	—	thermal T>100°C	—	—
	good	electrical current	—	—	chemical: solid
	very good	—	chemical: gaseous	—	chemical: liquid

Table IV

Useful energy		Time shift: storability			
		none	sufficient	good	very good
Shift in space	none	light, mechanical work, heat: T ~ 300°C information sector	—	—	—
	suff.	—	thermal (room heating) T~100°C	—	—
	good	—	—	—	—
	very good	—	—	—	—

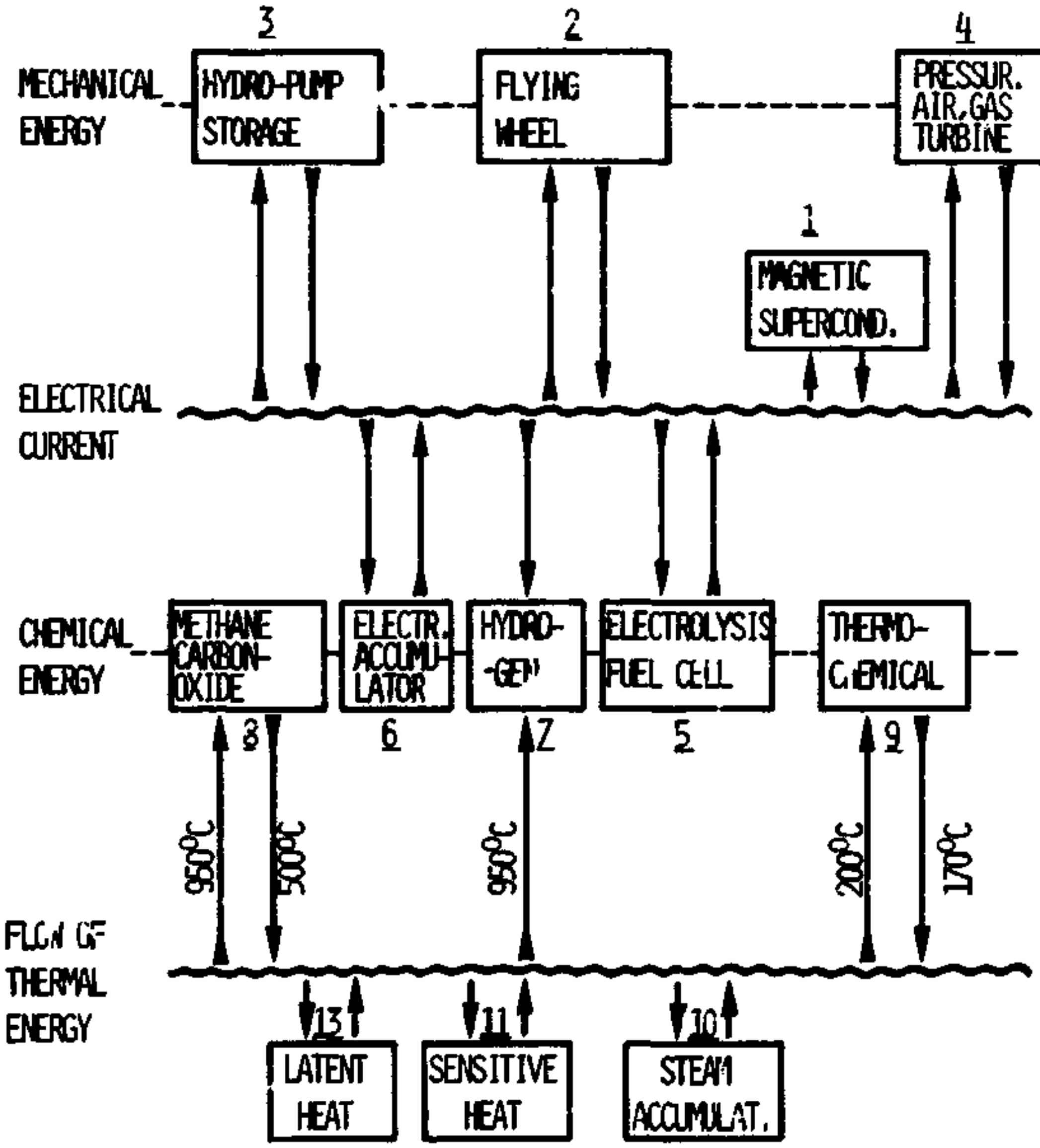

Fig. 3 Transformation of Secondary Energy for Storage and Transmission

The numbers refer to the lines in table VI.

The consumer wishes to get useful energy useful to him at the time and place he requires it. Often he does not want to move to reach a source of energy and he does not want to wait until his energy source fully operates. "Here and now" is the slogan of the energy consumer; moreover he requires the right form of energy.
The producer of secondary energy has by no means the same interest. He wants to produce energy which is economically profitable to him, and he wants to produce it regularly over a longer period of time and at a cental location if possible. The conflict between the two different interests is obvious.

5. TRANSFORMATION, STORAGE AND TRANSFER OF THE VARIOUS FORMS OF ENERGY

From table IV it can be seen that the best suitability for time and space shifts is found in those forms of energy which are not accessible to the consumer e.g. the nuclear energy carriers. Secondary energy must therefore take over the task of intermediary between the various forms of energy, and between the distributions of primary energy in time and space and the deman for useful energy.
Unfortunately, for technological, economical and historical reasons it is in many cases not so easy to store and to transfer secondary energy. In this respect the different forms of secondary energy vary considerably. They are listed in table V. The solution to this problem lies in an optimal connexion of all the three shifts in space, time and form. As a further analysis shows, this is a complex task with many parameters.
Fig. 3 is a simple diagram of the most used, and for the time being most hopeful methods of energy transformation, the goal being to considerably improve the capacity for storage and transport. The study is limited insofar as methods of transforming existing carriers of chemical energy into other forms of chemical energy are not treated.

Storability and Transportability of Secondary Energy — Table V

		Storability			
		none	sufficient	good	very good
Transferability	none	mechanical work*) light*) sensitive thermal energy $T<100^\circ C$	latent thermal energy: $T<100^\circ C$	thermo- chemical energy: $T<200^\circ C$	
	suff.		thermal energy: $T>100^\circ C$	electro- chemical energy: (accumulators)	
	good	electrical current		thermo- chemical energy: $T>500^\circ C$	chemical energy solid: (coal**)
	very good			chemical energy gaseous: (natural gas**) synthetic hydrogen	chemical energy fluid (mineral oil) synthetic hydrocarbon

*) only as useful energy; no secondary energy

**) natural fossil fuel: coal, oil, gas, but probably at exhaution limit

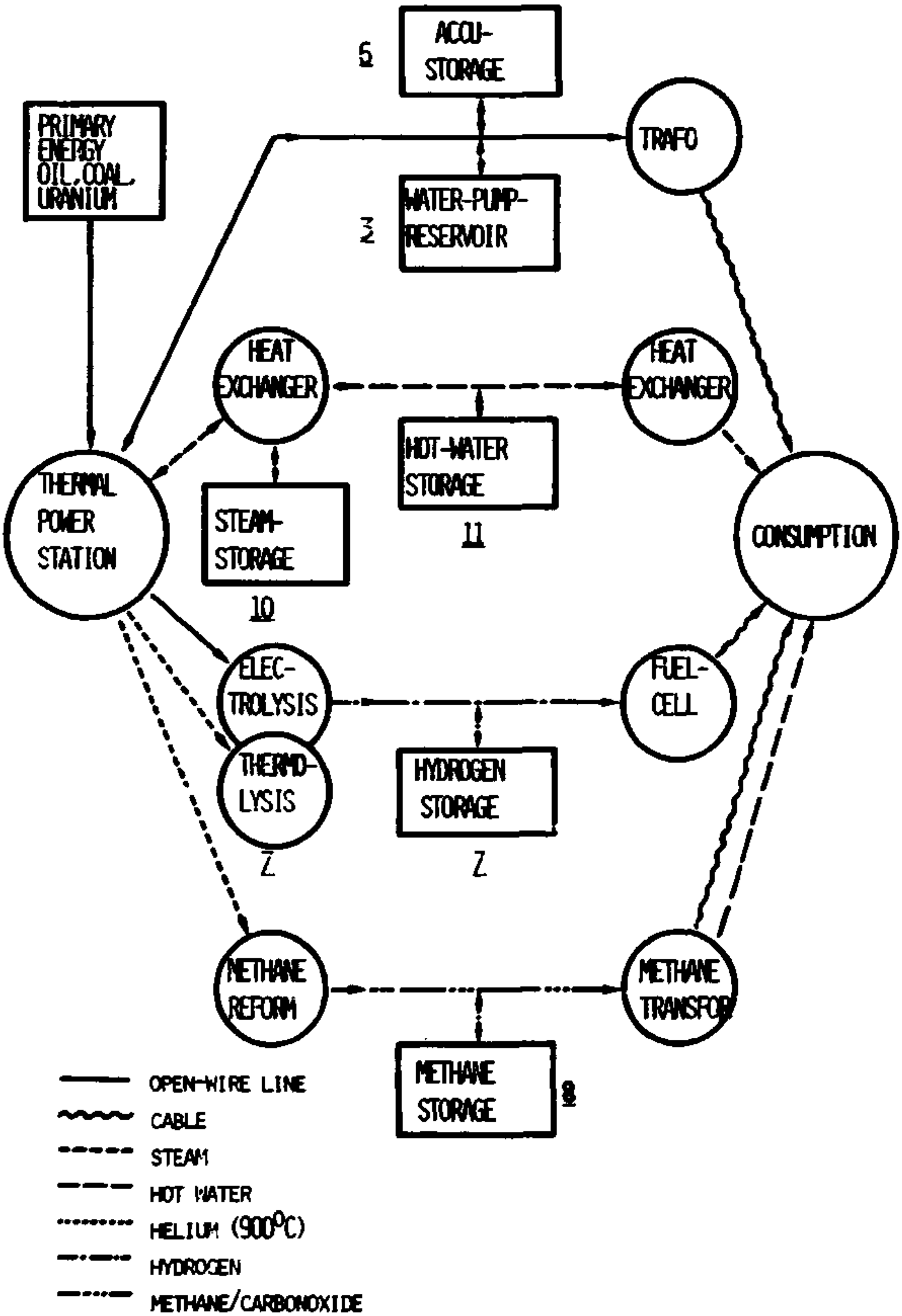

Fig. 4 Example of Storage and Transport of Secondary Energy
The numbers refer to fig. 3 and table VI.

With the aid of an extensive example will be illustrated the transformation of secondary energy from chemical or nuclear fuel into various forms of secondary energy which can be stored and transported to the user (fig. 4).

6. STORAGE ANO TRANSMISSION METHODS

One of the difficulties in studying the problems of storage and transport of secondary energy is the abundance of technologies, which are proposed, developed and already operating on a large scale. Incomplete representations of technologies often render comparisons difficult. Nevertheless we try to recapitulate the most important properties of the respective installations and to possibly reduce them to a common denominator.

Table VI is a survey of the most important storage technologies. They are listed in decreasing quality order, i.e. increasing entropy. It starts with electrical energy and leads over chemical to thermal forms of energy.

Analogically, table VII lists the most important transport technologies.

7. RELATIVE COST OF STORAGE AND TRANSMISSION

The references which can also be found in literature, regarding capital and operating cost of stored as well as transferred energy vary highly depending on many parameters, particularly on local circumstances. Nevertheless relative cost can be listed in a logarithmic scale as shown in fig. 5.

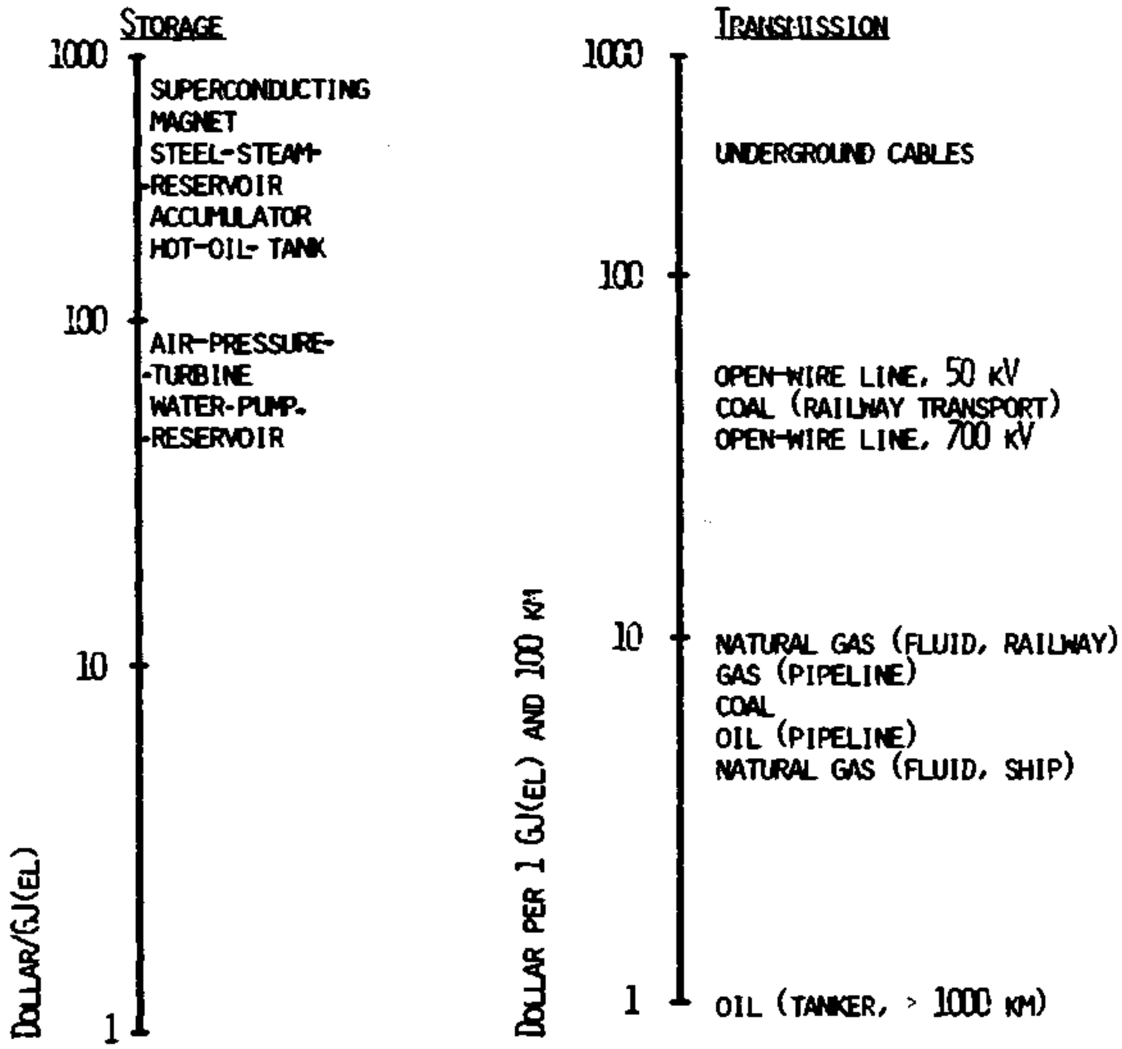

Fig. 5 Cost for 1 GJ(el) Storage resp. transmission per 100 km distance

No. in fig.3	Kind of transformation: input	Kind of transformation: output	in storage	Station and its economical size: MW(el) or MWh(el)	Cost(1978) $/kW / $/kWh	State of technology	Efficiency % / lifetime years(y)	Specific prop: under- resp. overground	Specific prop: geologica geography parameter
1	electr.	electr.	magnetic	superconducting magnet 10 000 MWh	50....60 / 30...140	research	< 70 % / < 25 y	above	none
2	electr.	electr.	mechanic	flywheel 10-50 MWh	65....75 / 100..300	research	> 70 % / 25 y	above	none
3	electr.	electr.	mechanic, gravitation	water reservoir pumps 200-2000 MW	90...160 / 2.....12	large scale	< 70 % / < 50 y	above	water bas 100
4	electr.	electr.	mechanic + chemical	pressurized air 200-1000 MW	100...210 / 4......30	large scale	? / < 25 y	under	big leak-proof cav
5	electr.	electr.	chemical	electrolyzer and fuel cell ∿ 10 MW(el)		development	50 % / ∿ 10 y	under	none
6	electr.	electr.	chemical	future accumulator 20-50 MWh	60.....70 / 20.....60	development	< 80 % / < 20 y	above	none
7	electr.	chemical	chemical	hydrogen reservoir 20-50 MW	500...900 / 6......15	development	< 50 % / < 20 y	above / under	none / leakproof cavern

8	thermal thermal	chemical	synthesis gas: methane-reservoir		research	< 90 % < 20 y		
9	thermal thermal	chemical	thermo-chemical reservoir < 800 MWh		research	< 85 % < 30 y	above	none
10	thermal thermal	thermal + pres- sure	steam accumulator 50 - 200 MW	150....250 30.....70	industrial scale	< 75 % 25 y	above under	cast iron leakproof rock
11	thermal thermal	sensitive	hot water, hot sand		development	< 90 % ?	above	deep flaw
12	thermal thermal	latent heat	molten-salt accumulator: < 500 MWh		research	< 90 % < 25 y	under	

Compilation of the most important transport technologies

No. in fig. 3	Kind of transformation: input / output	Kind of transformation: form of transport	Station	State of technology %	Effi-ciency	Specific properties: under-resp. aboveground	Specific properties: geological or geographical parameters	pre (
0	electrical electrical	electrical current	electrical open-wire line	large scale	90	above	none	~1
0	electrical electrical	electrical current	electrical cable line	large scale	95	under	none	O S u p
0	electrical electrical	electrical current	electrical line cable, superconductor	research	95	under	none	h c
5	electrical electrical	chemical	electrolyzer and fuel cell	development	~50	under	none	<1
6	electrical electrical	electro-chemical	high-temperature accumulator	development	<70	for vehicles	none	~1
7	electrical chemical	chemical	hydrogen-pipeline	small scale	~97	under	none	<5
8	thermal thermal	chemical	synthetic-gas; methane; pipeline	development	~90	under	none	<7

9	thermal thermal	chemical	thermochemical in waggons	research	∼85	railway waggons	railway lines	<1
10	thermal thermal	sensitive	hot-water-pipeline (closed)	large scale	∼90	under	none	<1
11	thermal thermal	sensitive heat	warm-water-pipeline (open)	development	∼90	under	none	∼1
12	thermal thermal	latent heat	molten-salt-pipeline (closed)	research	∼90	under	none	∼1

8. CONCLUSIONS

1. Storage technology and transmission technology are very complex problems which are related to numerous marginal conditions. The given specific conditions in space and time play a decisive role.

2. The best form of secondary energy from the viewpoint of storage and transmission is the chemical energy, e.g. gaseous (hydrogen) or, even better, liquid hydrocarbons. The advantages of these energy carriers are all the more clearer since for example hydrocarbons can also be found in nature, i.e. in the form of stored primary energy.

3. New sources of primary energy, such as solar energy, wind energy, tidal energy can be transformed into a form of secondary energy only with a big effort which has good storage and transmission properties.

4. The highest quality secondary energy, electrical energy (also from nuclear primary energy) is relatively unsuited for storage.

5. The optimization of the total energy economy depends to a large extent on the improvement of the storage and transmission efficiency.

6. Only a large scale of different technologies in the energy storage and energy transmission field can bring about a significant improvement of the energy economy.

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