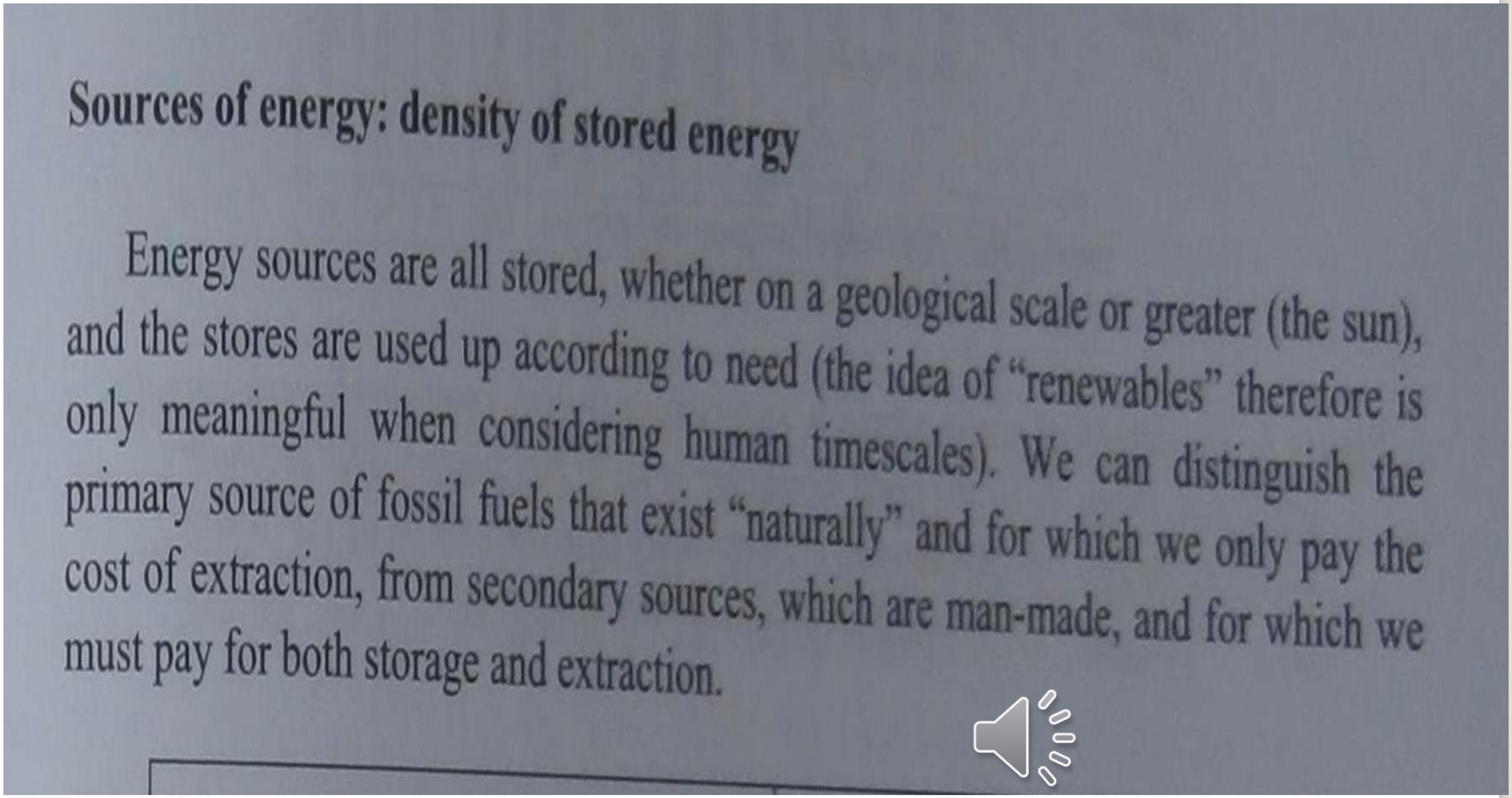
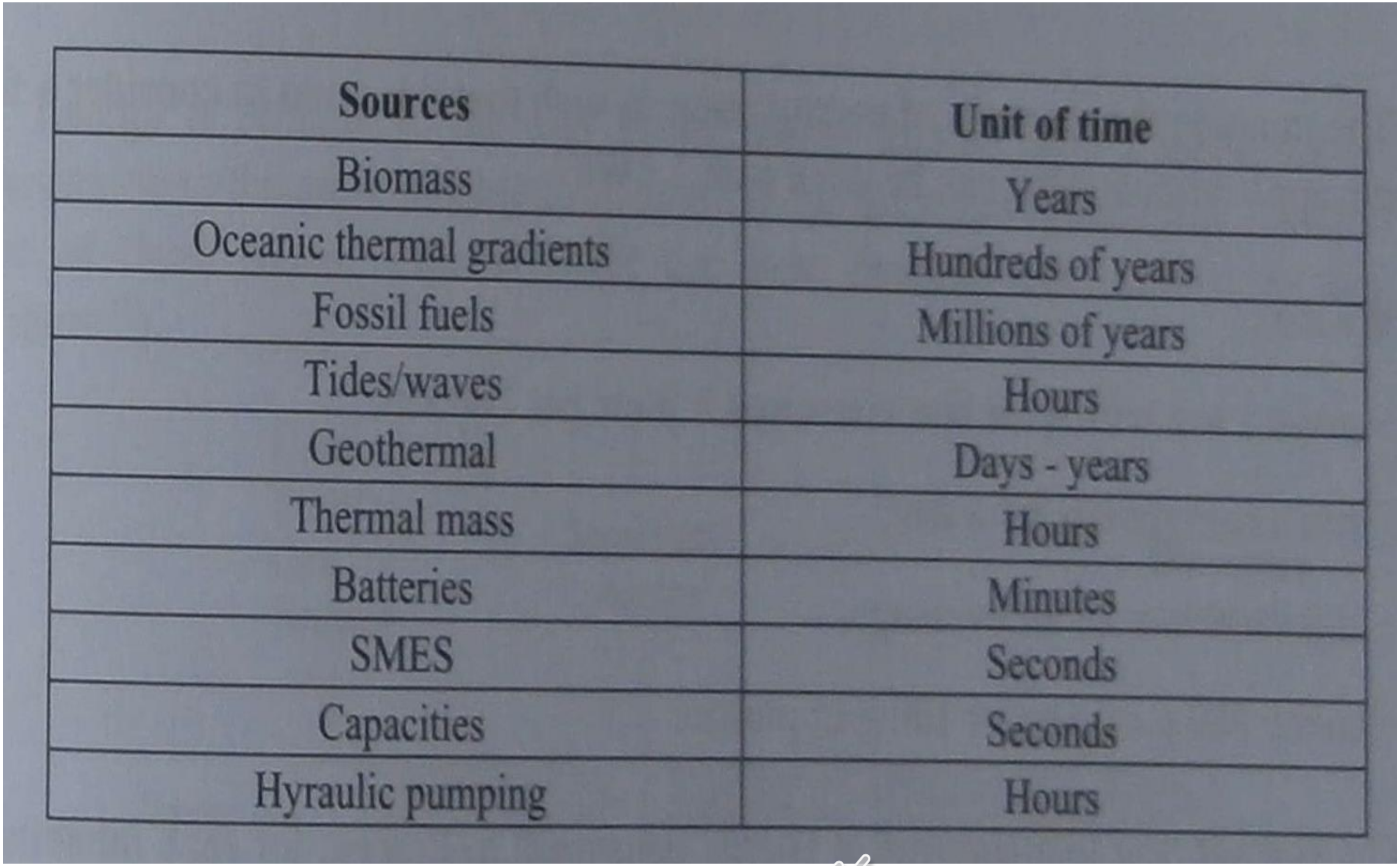
(2) Current energy storage technologies & their applications

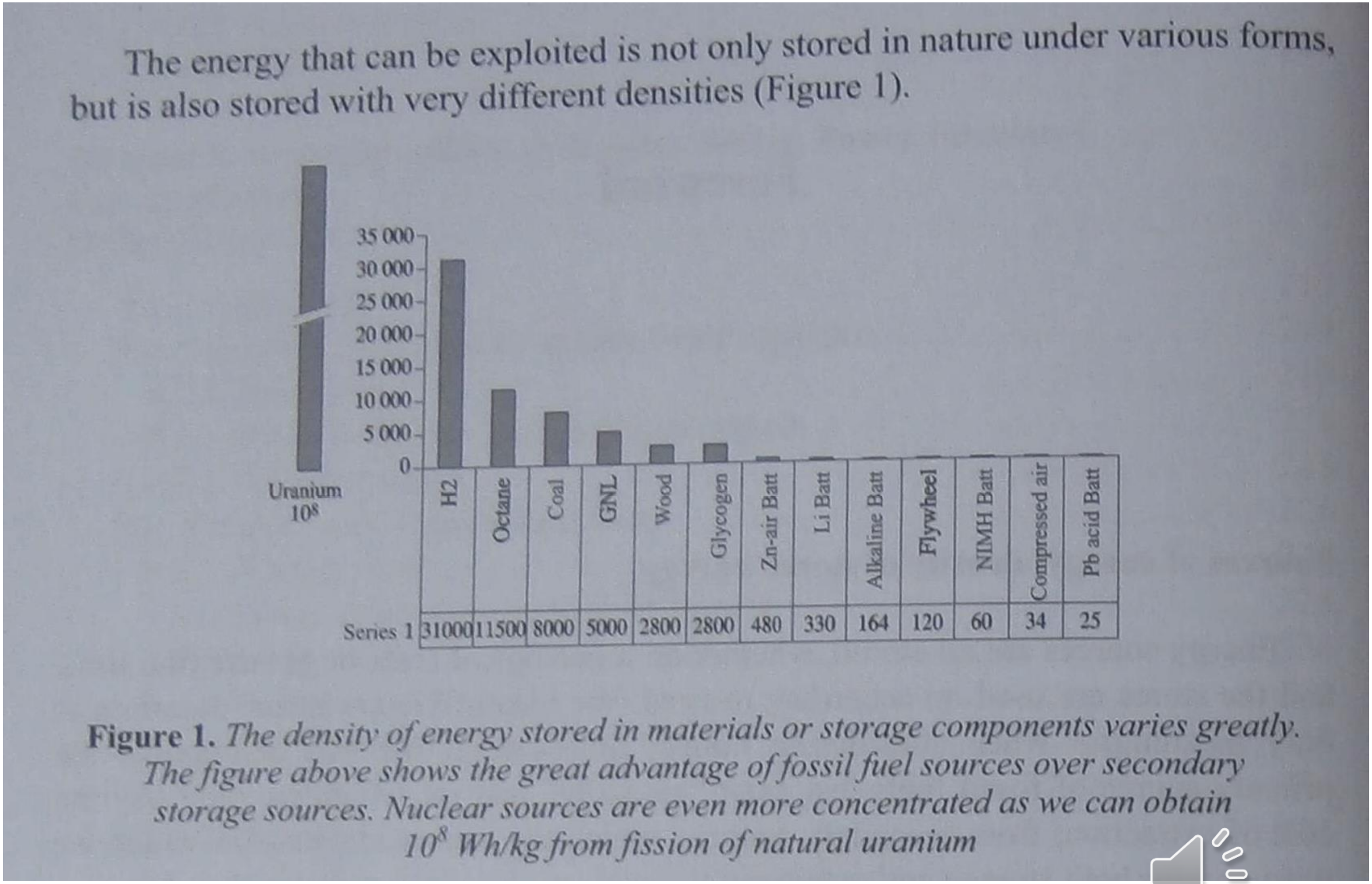


Sources of energy: density of stored energy

Energy sources are all stored, whether on a geological scale or greater (the sun), and the stores are used up according to need (the idea of "renewables" therefore is only meaningful when considering human timescales). We can distinguish the primary source of fossil fuels that exist "naturally" and for which we only pay the cost of extraction, from secondary sources, which are man-made, and for which we must pay for both storage and extraction.



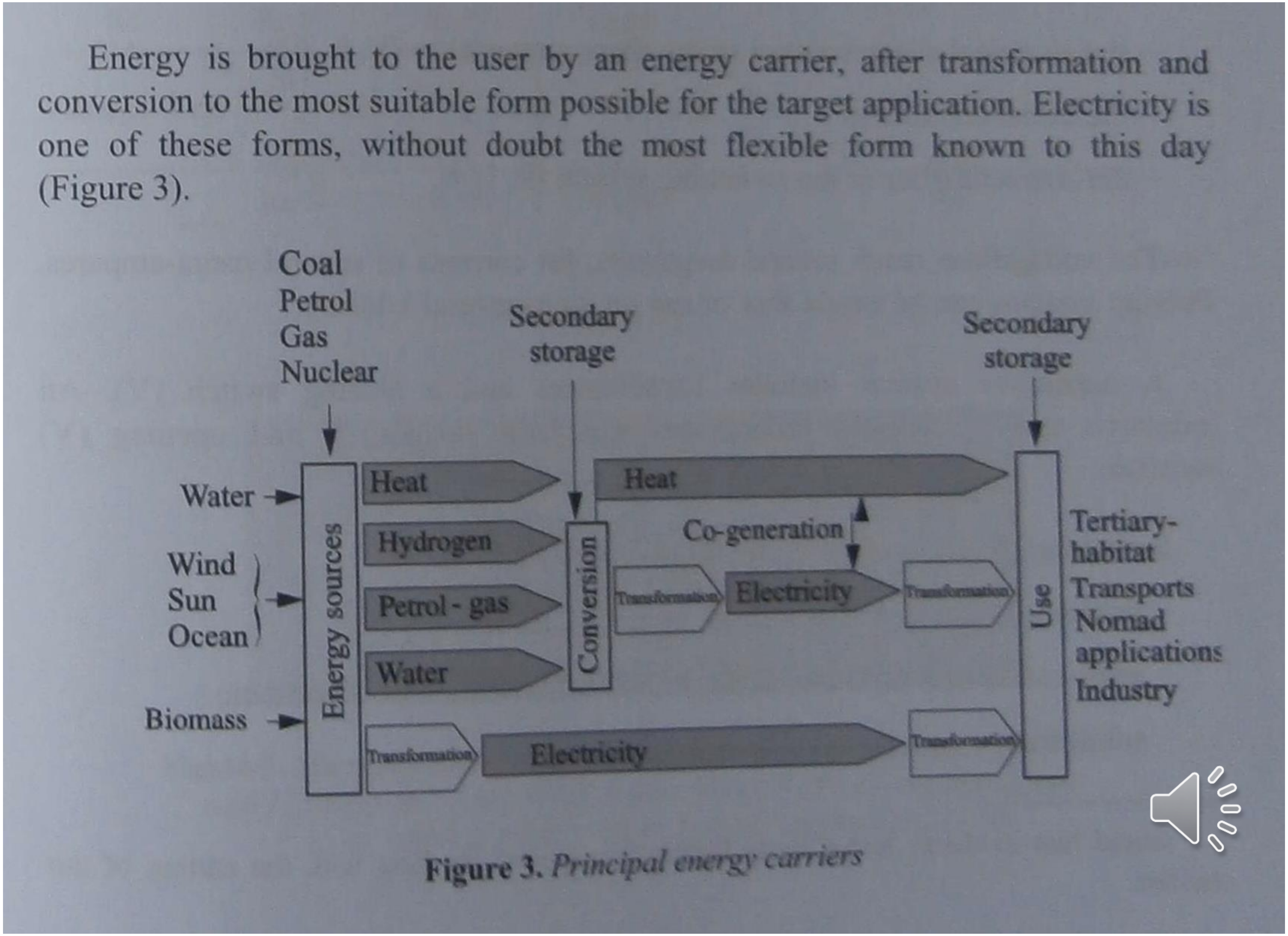
Sources	Unit of time
Biomass	Years
Oceanic thermal gradients	Hundreds of years
Fossil fuels	Millions of years
Tides/waves	Hours
Geothermal	Days - years
Thermal mass	Hours
Batteries	Minutes
SMES	Seconds
Capacities	Seconds
Hyraulic pumping	Hours



The energy that can be exploited is not only stored in nature under various forms, but is also stored with very different densities (Figure 1).

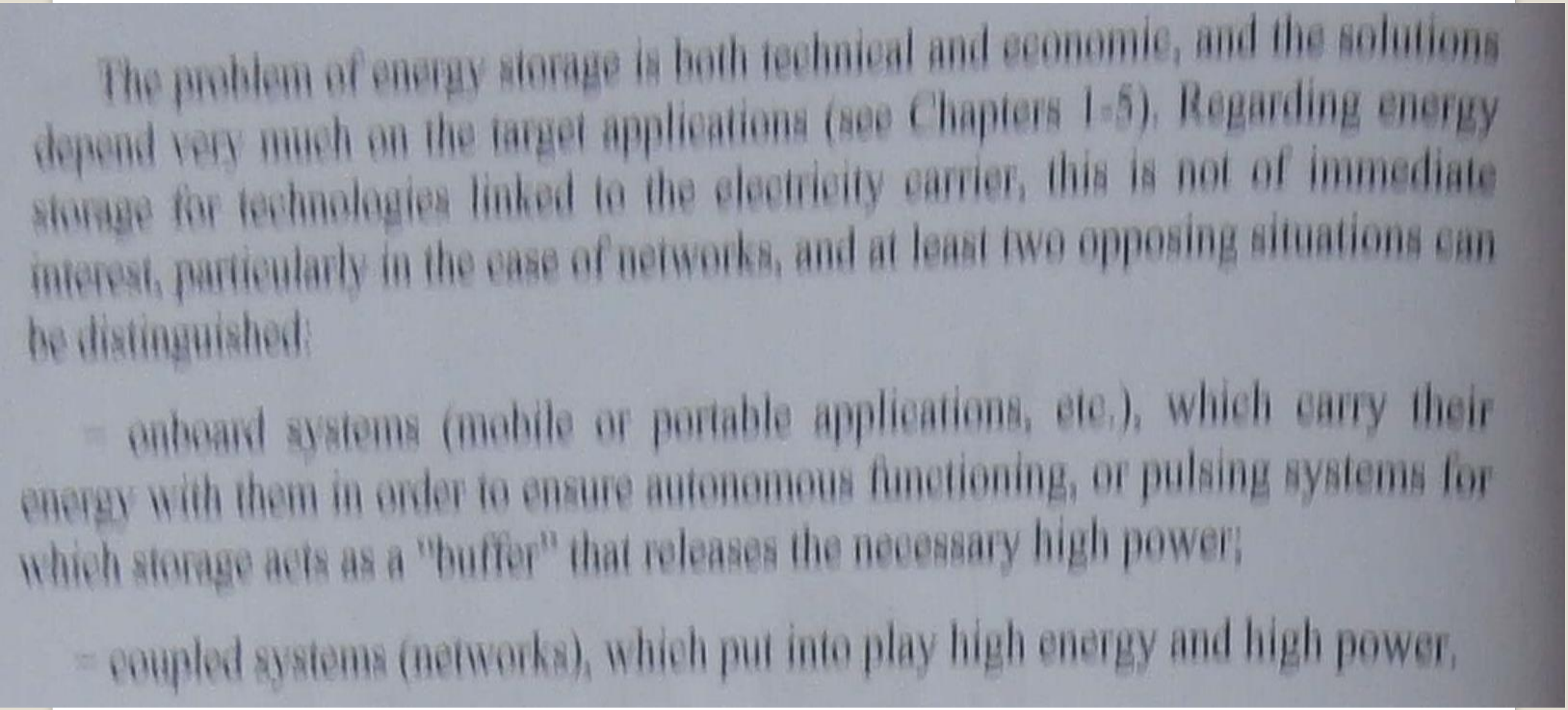
	H2	Octane	Coal	GNL	Wood	Glycogen	Zn-air Batt	Li Batt	Alkaline Batt	Flywheel	NIMH Batt	Compressed air	Pb acid Batt
Series 1	31000	11500	8000	5000	2800	2800	480	330	164	120	60	34	25

Figure 1. *The density of energy stored in materials or storage components varies greatly. The figure above shows the great advantage of fossil fuel sources over secondary storage sources. Nuclear sources are even more concentrated as we can obtain 10^8 Wh/kg from fission of natural uranium*



Energy is brought to the user by an energy carrier, after transformation and conversion to the most suitable form possible for the target application. Electricity is one of these forms, without doubt the most flexible form known to this day (Figure 3).

Figure 3. *Principal energy carriers*

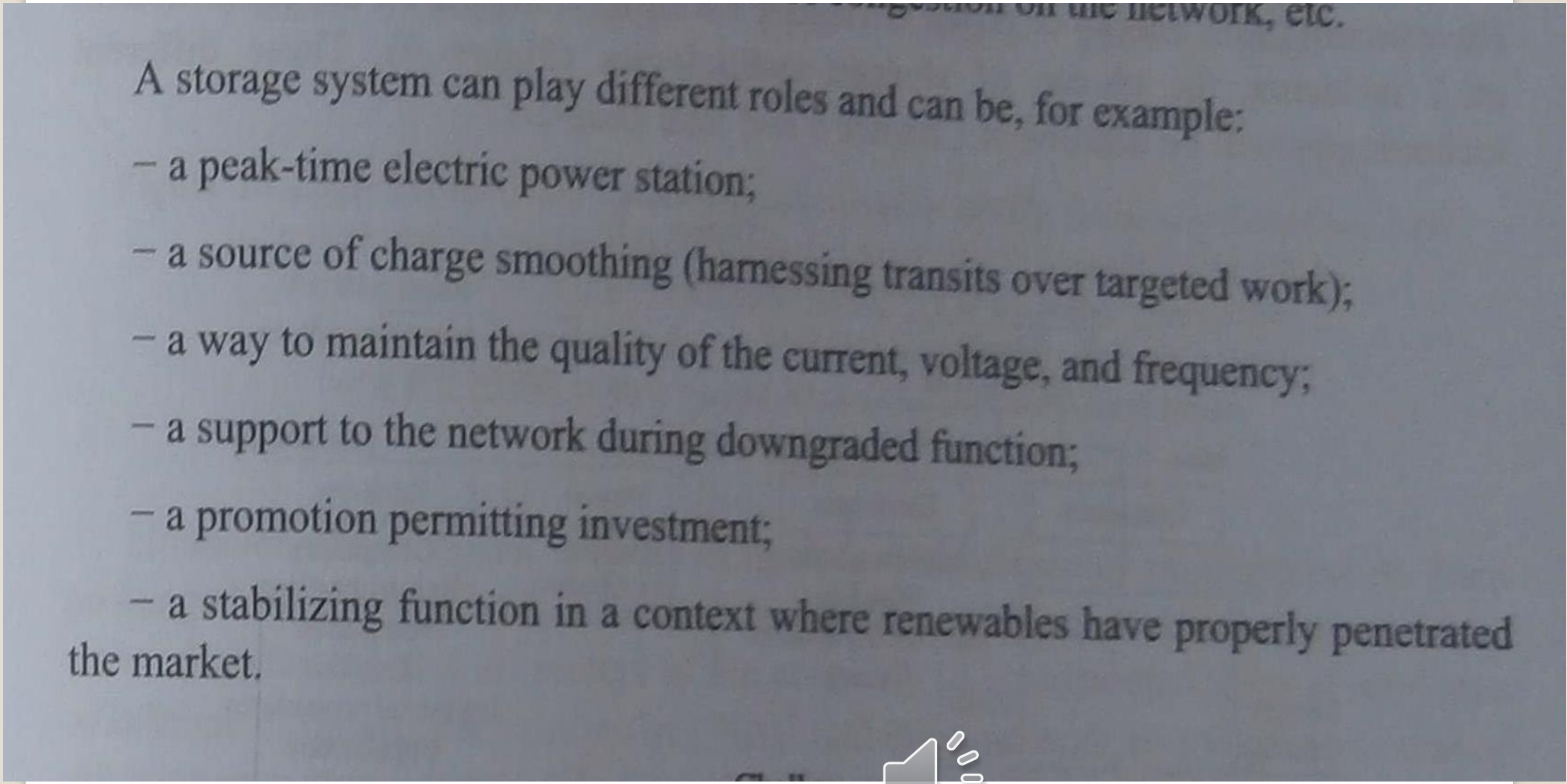


The problem of energy storage is both technical and economic, and the solutions depend very much on the target applications (see Chapters 1-5). Regarding energy storage for technologies linked to the electricity carrier, this is not of immediate interest, particularly in the case of networks, and at least two opposing situations can be distinguished:

– onboard systems (mobile or portable applications, etc.), which carry their energy with them in order to ensure autonomous functioning, or pulsing systems for which storage acts as a "buffer" that releases the necessary high power;

– coupled systems (networks), which put into play high energy and high power,

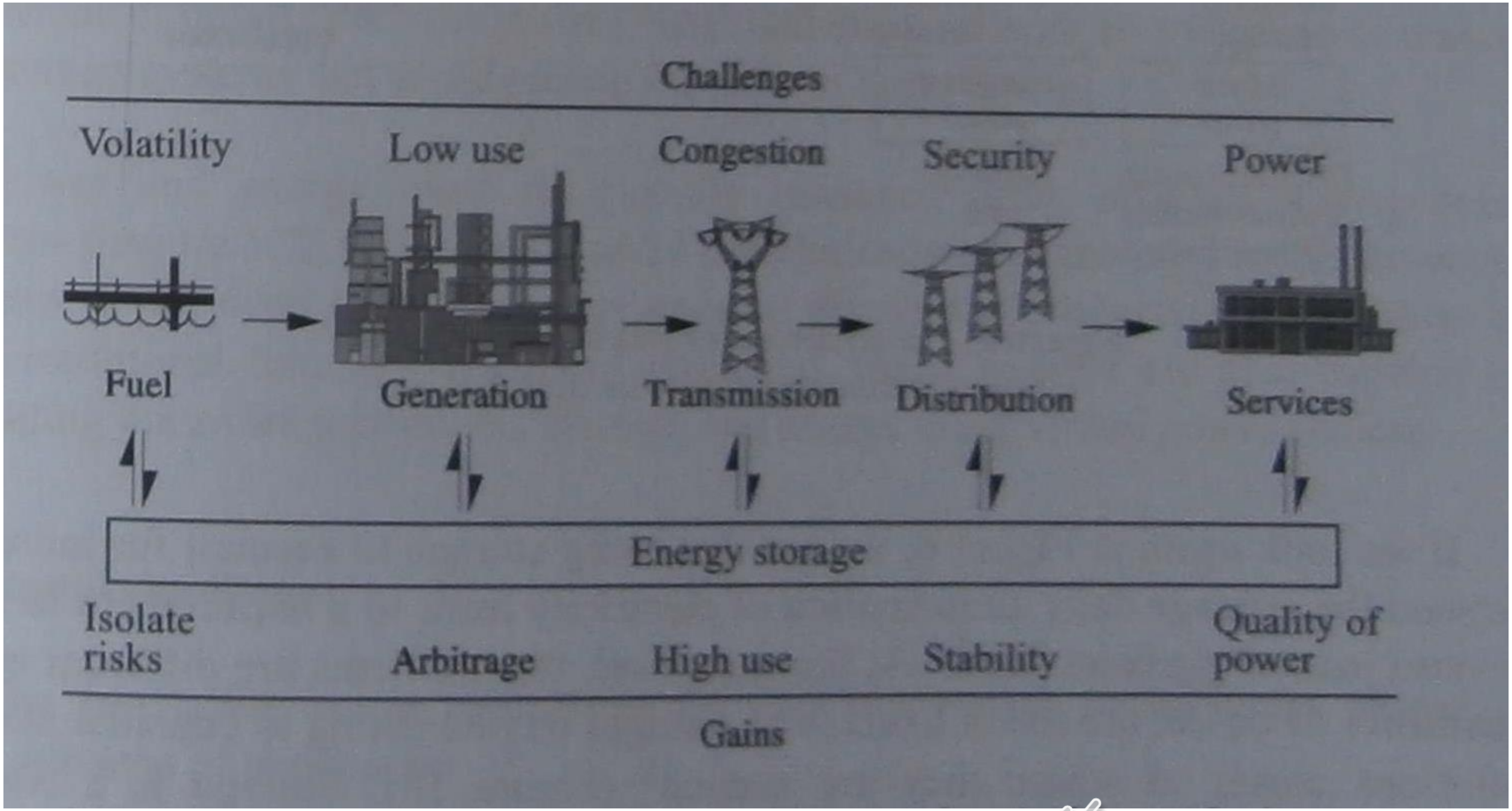
Read--- Special Case Pulsating System



on the network, etc.

A storage system can play different roles and can be, for example:

- a peak-time electric power station;
- a source of charge smoothing (harnessing transits over targeted work);
- a way to maintain the quality of the current, voltage, and frequency;
- a support to the network during downgraded function;
- a promotion permitting investment;
- a stabilizing function in a context where renewables have properly penetrated the market.


Challenges
Volatility
Low use
Congestion
Security
Power
Fuel
Generation
Transmission
Distribution
Services
Energy storage
Isolate risks
Arbitrage
High use
Stability
Quality of power
Gains

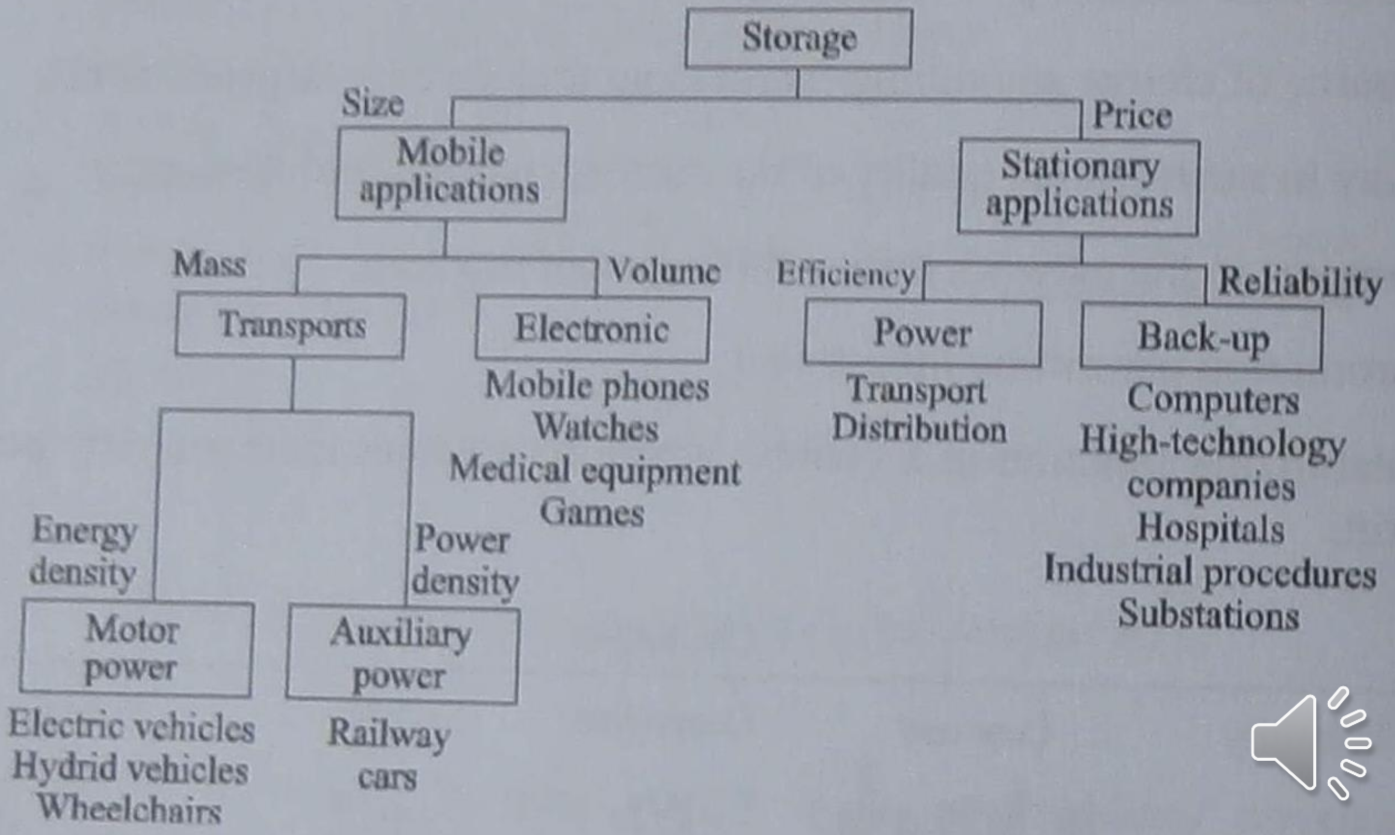
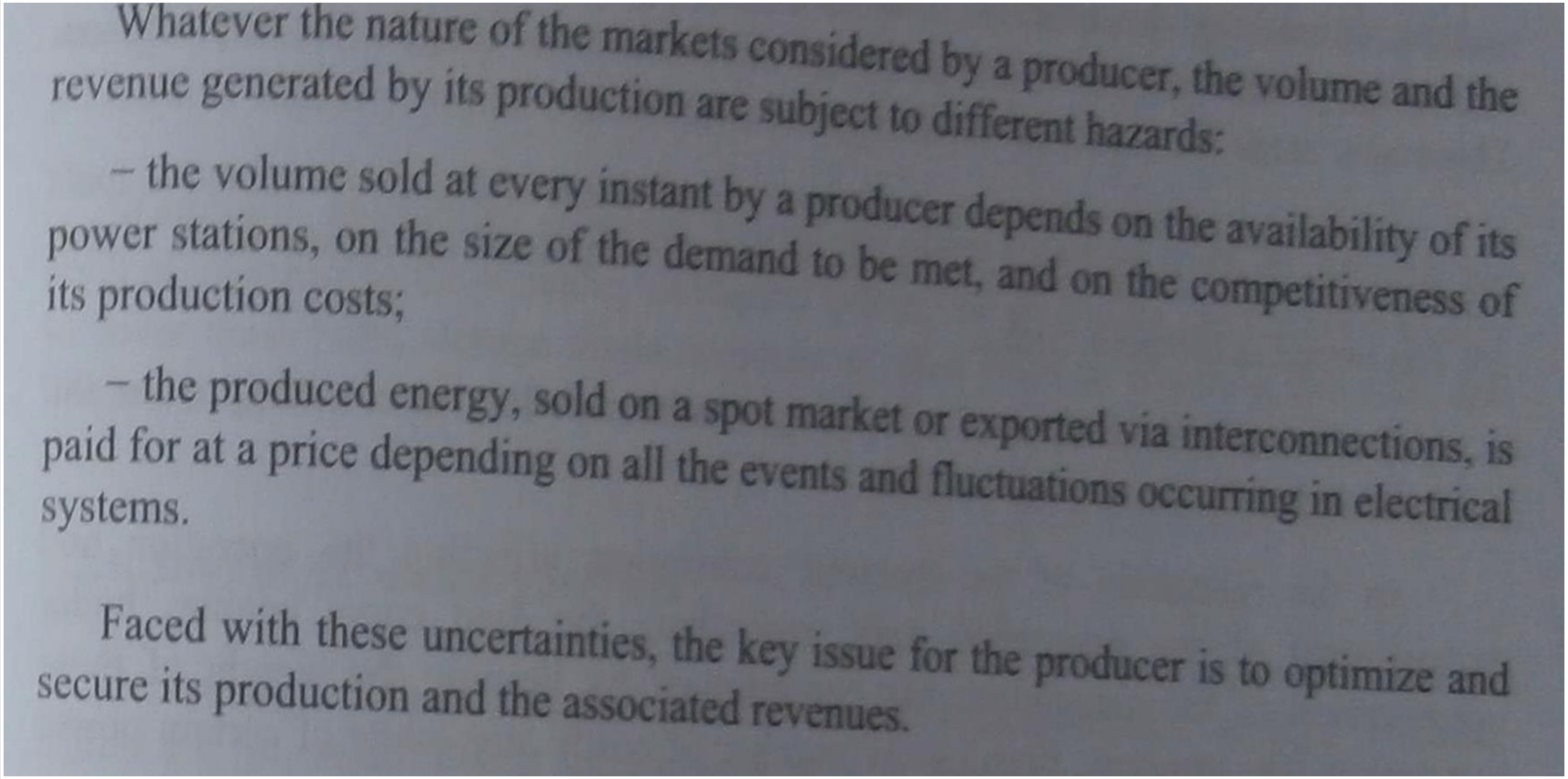


Figure 9. *Constraints and criteria for choosing storage technology based on applications*

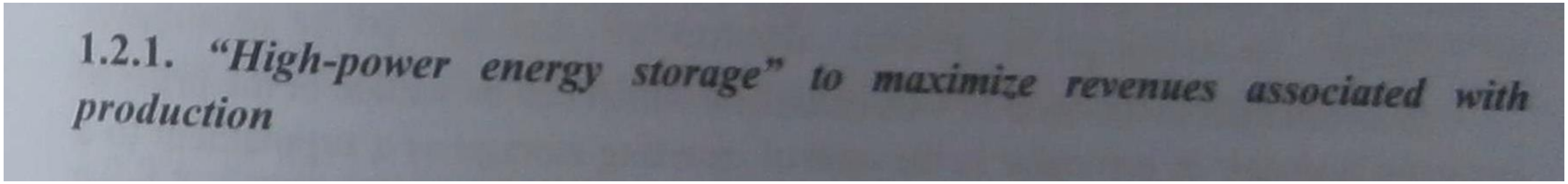


Whatever the nature of the markets considered by a producer, the volume and the revenue generated by its production are subject to different hazards:

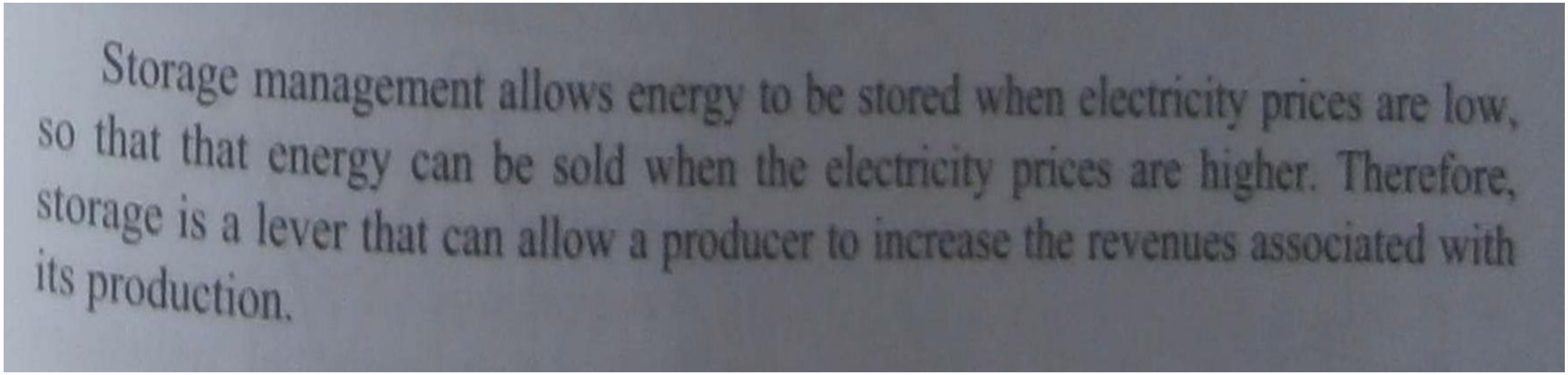
– the volume sold at every instant by a producer depends on the availability of its power stations, on the size of the demand to be met, and on the competitiveness of its production costs;

– the produced energy, sold on a spot market or exported via interconnections, is paid for at a price depending on all the events and fluctuations occurring in electrical systems.

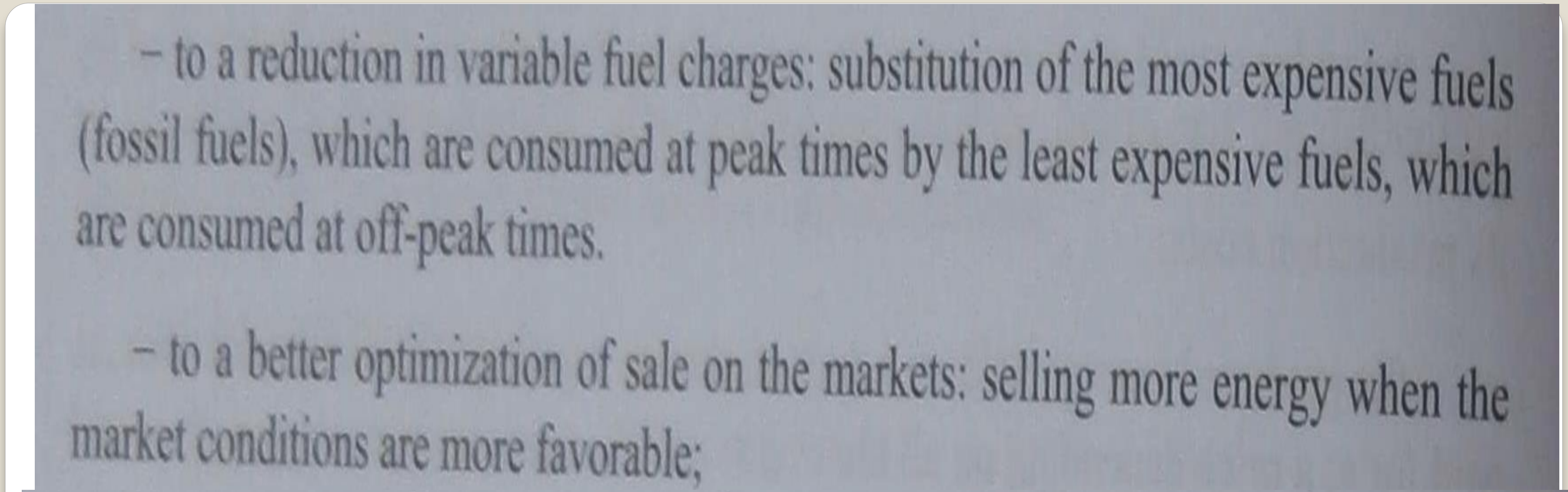
Faced with these uncertainties, the key issue for the producer is to optimize and secure its production and the associated revenues.



1.2.1. *“High-power energy storage” to maximize revenues associated with production*

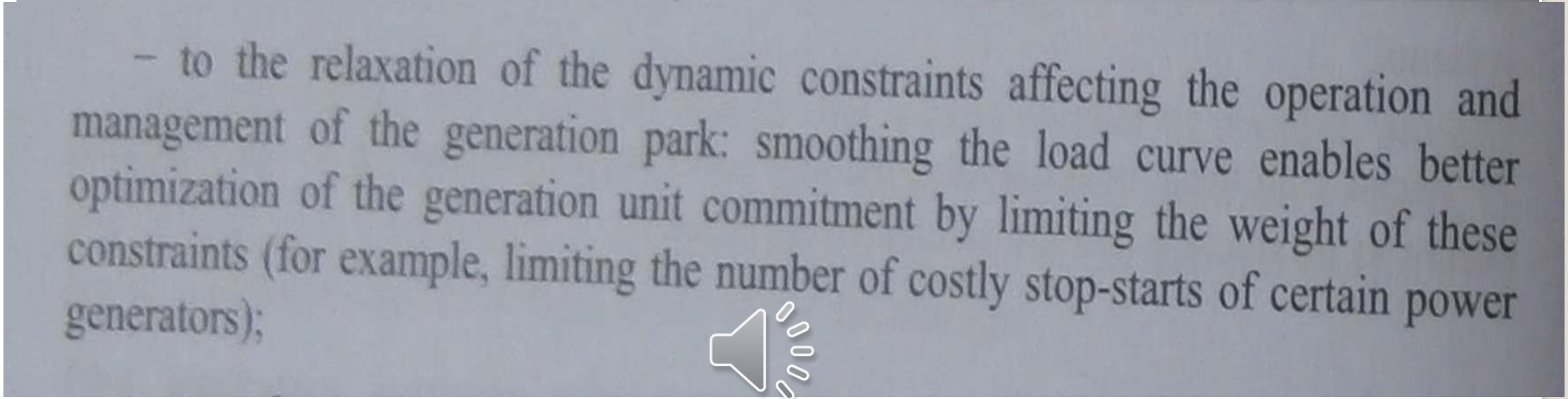


Storage management allows energy to be stored when electricity prices are low, so that that energy can be sold when the electricity prices are higher. Therefore, storage is a lever that can allow a producer to increase the revenues associated with its production.

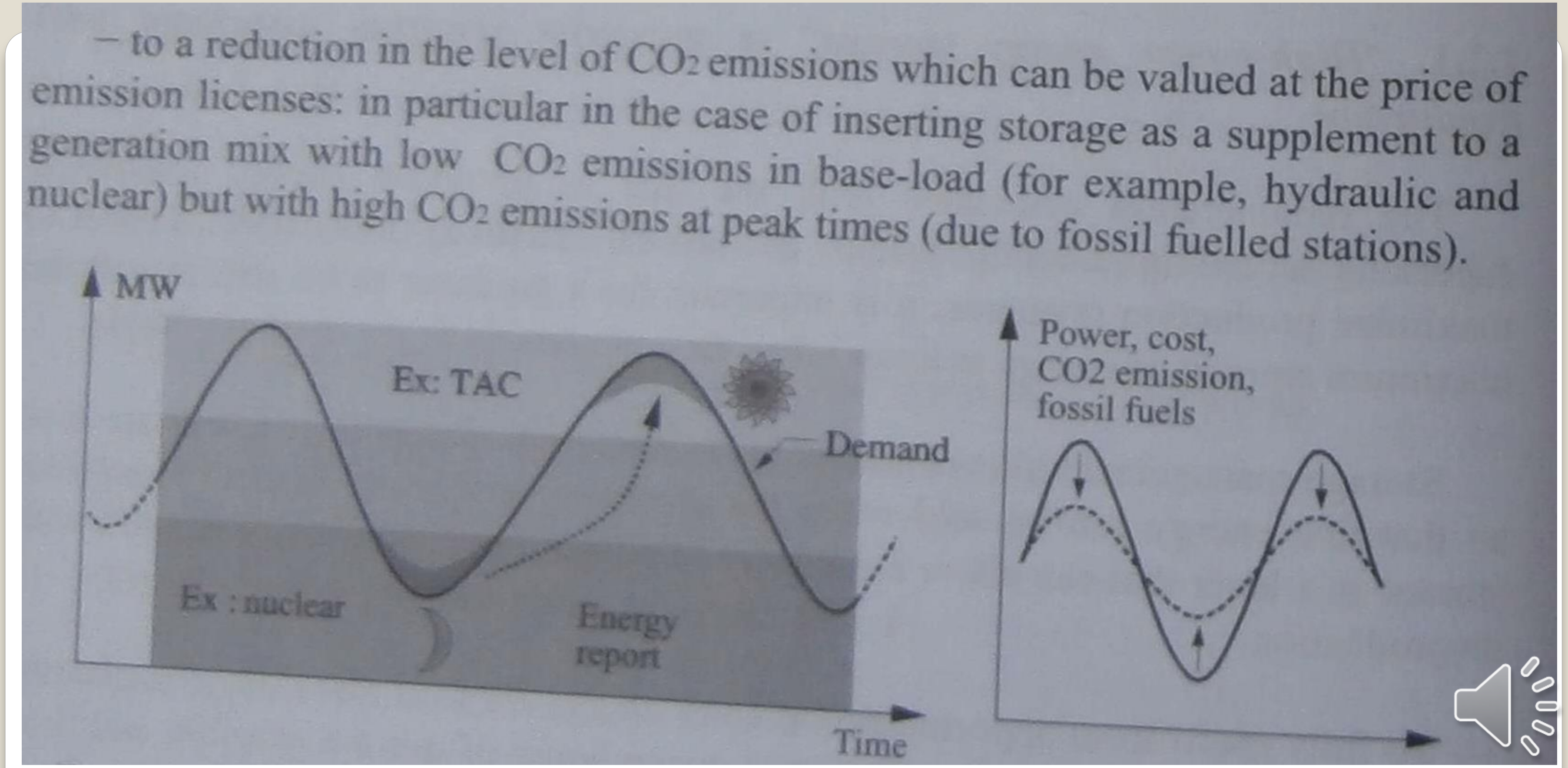


– to a reduction in variable fuel charges: substitution of the most expensive fuels (fossil fuels), which are consumed at peak times by the least expensive fuels, which are consumed at off-peak times.

– to a better optimization of sale on the markets: selling more energy when the market conditions are more favorable;

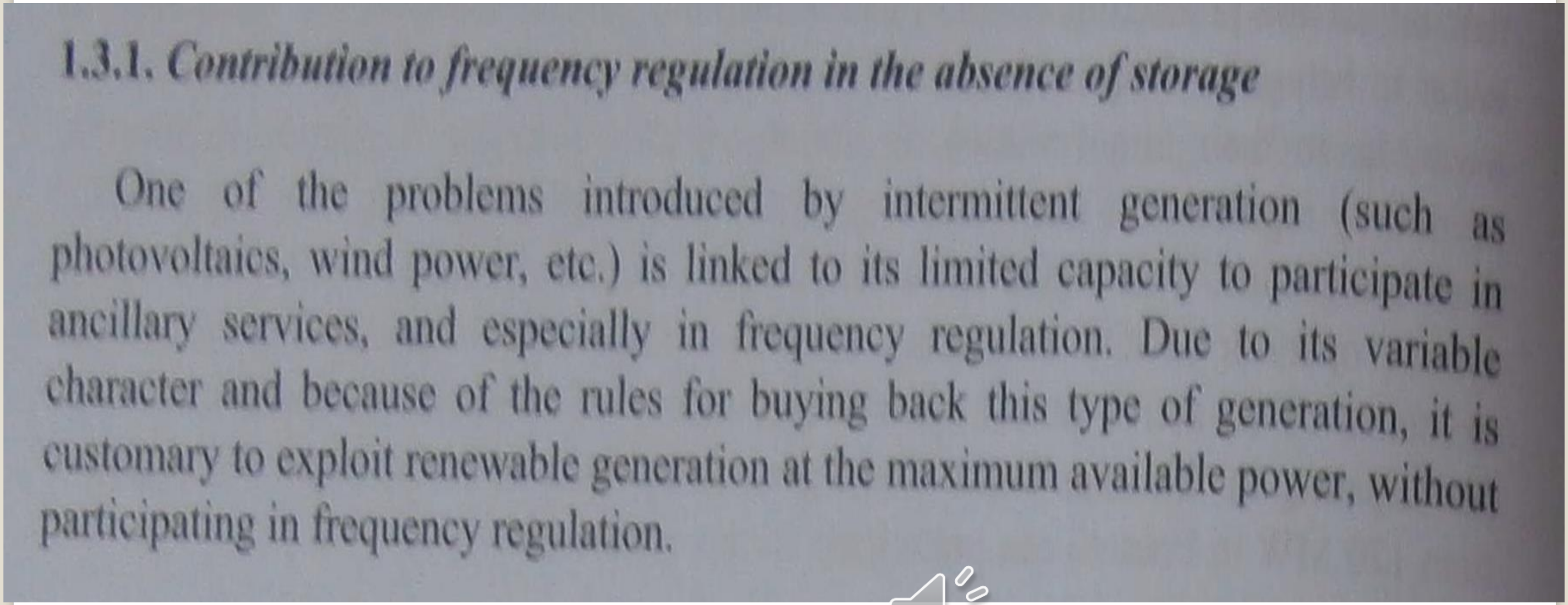


– to the relaxation of the dynamic constraints affecting the operation and management of the generation park: smoothing the load curve enables better optimization of the generation unit commitment by limiting the weight of these constraints (for example, limiting the number of costly stop-starts of certain power generators);



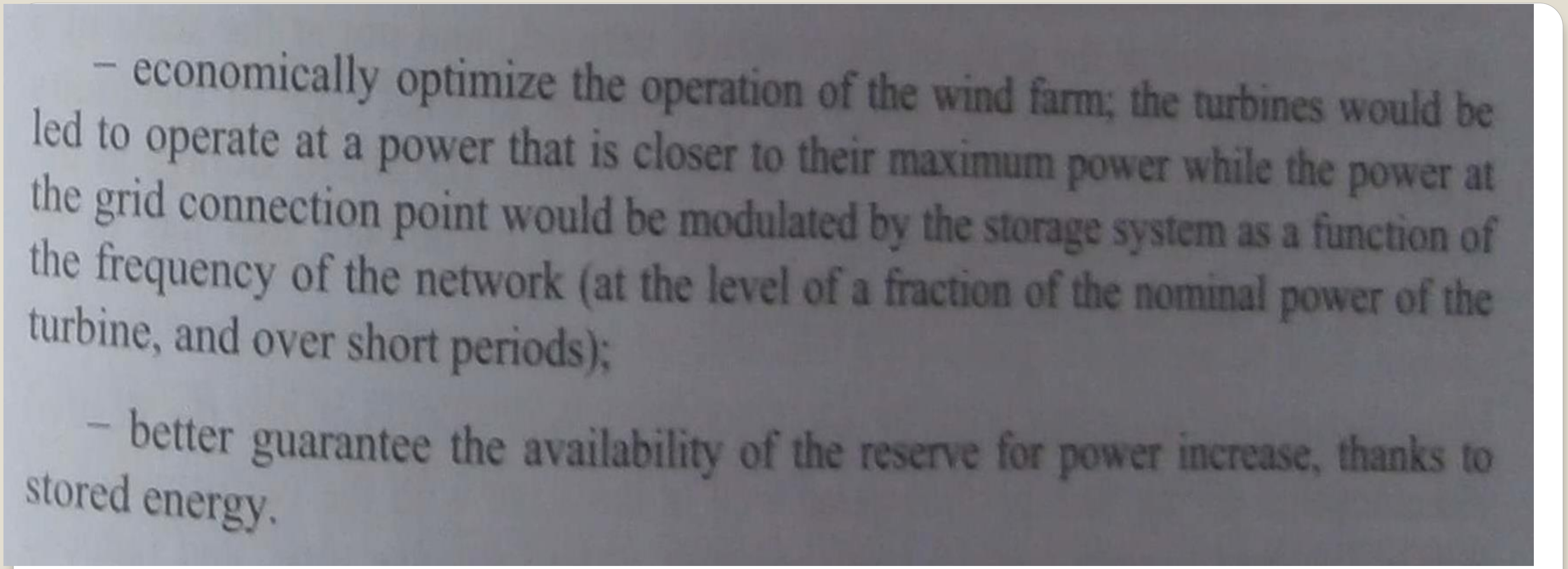
– to a reduction in the level of CO_2 emissions which can be valued at the price of emission licenses: in particular in the case of inserting storage as a supplement to a generation mix with low CO_2 emissions in base-load (for example, hydraulic and nuclear) but with high CO_2 emissions at peak times (due to fossil fuelled stations).

- Frequency Regulation
- Steady State Power Frequency Characteristics
- Tertiary Frequency Regulation
- Restoration of Network



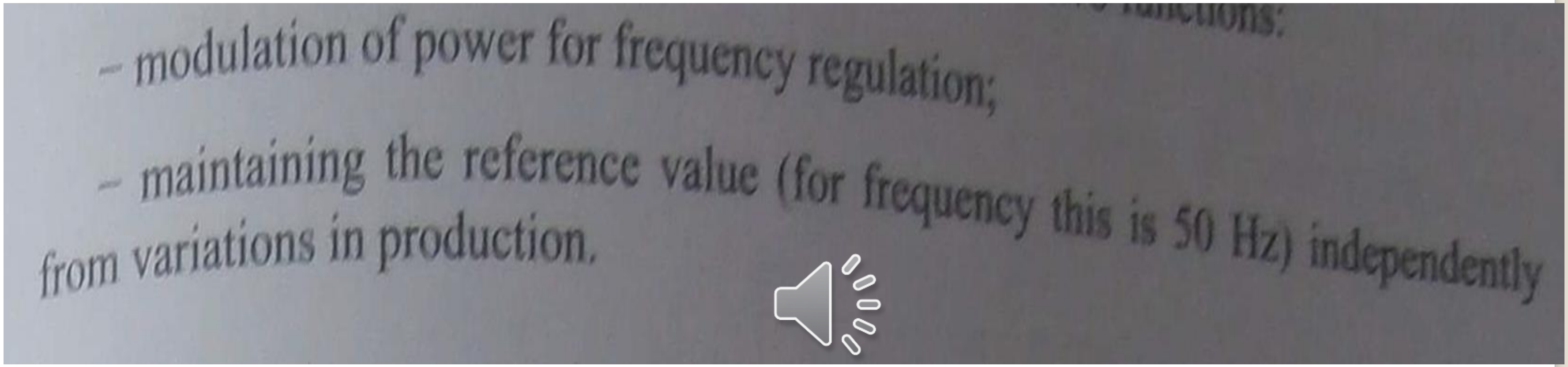
1.3.1. *Contribution to frequency regulation in the absence of storage*

One of the problems introduced by intermittent generation (such as photovoltaics, wind power, etc.) is linked to its limited capacity to participate in ancillary services, and especially in frequency regulation. Due to its variable character and because of the rules for buying back this type of generation, it is customary to exploit renewable generation at the maximum available power, without participating in frequency regulation.



– economically optimize the operation of the wind farm; the turbines would be led to operate at a power that is closer to their maximum power while the power at the grid connection point would be modulated by the storage system as a function of the frequency of the network (at the level of a fraction of the nominal power of the turbine, and over short periods);

– better guarantee the availability of the reserve for power increase, thanks to stored energy.



unctions:

– modulation of power for frequency regulation;

– maintaining the reference value (for frequency this is 50 Hz) independently from variations in production.

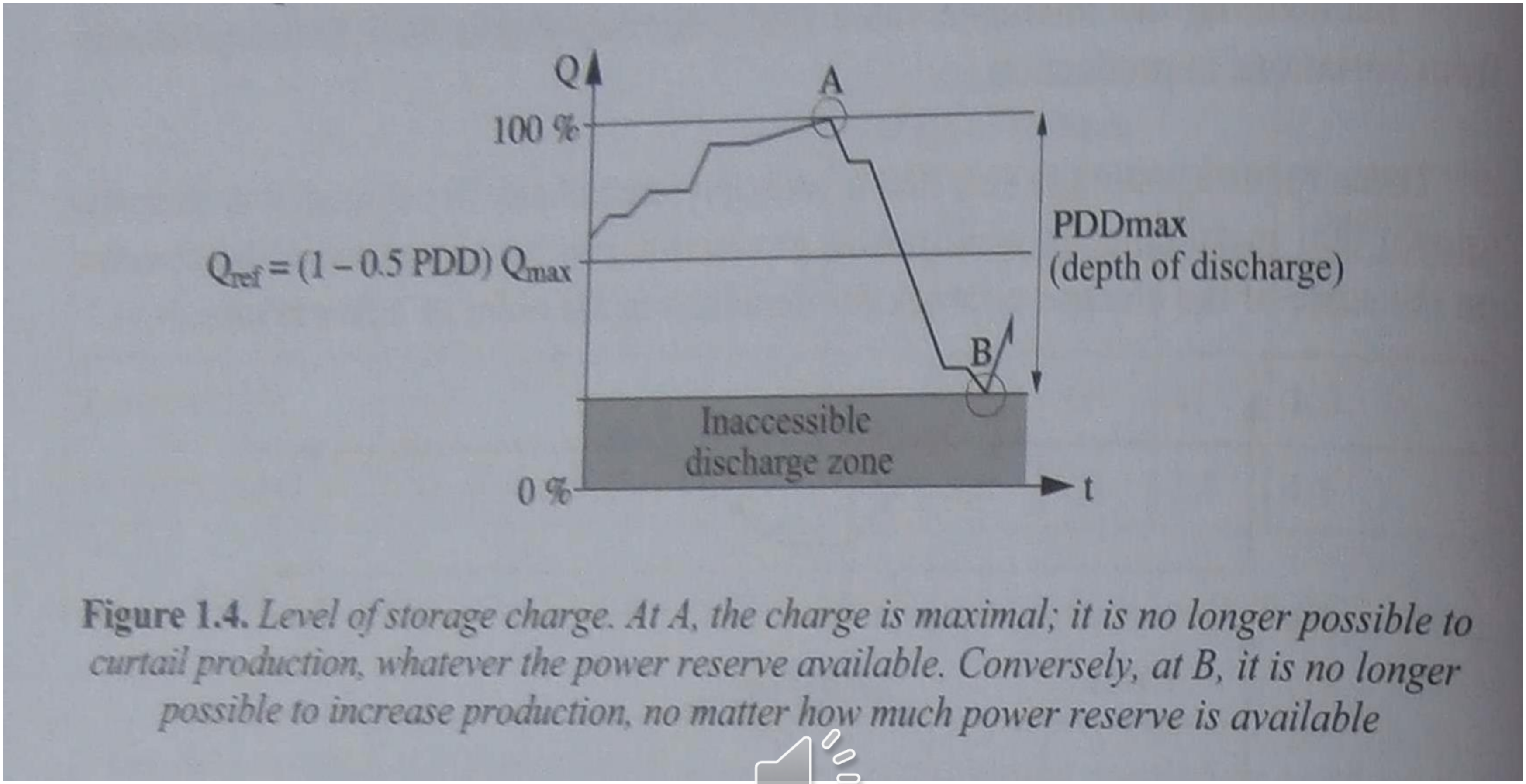
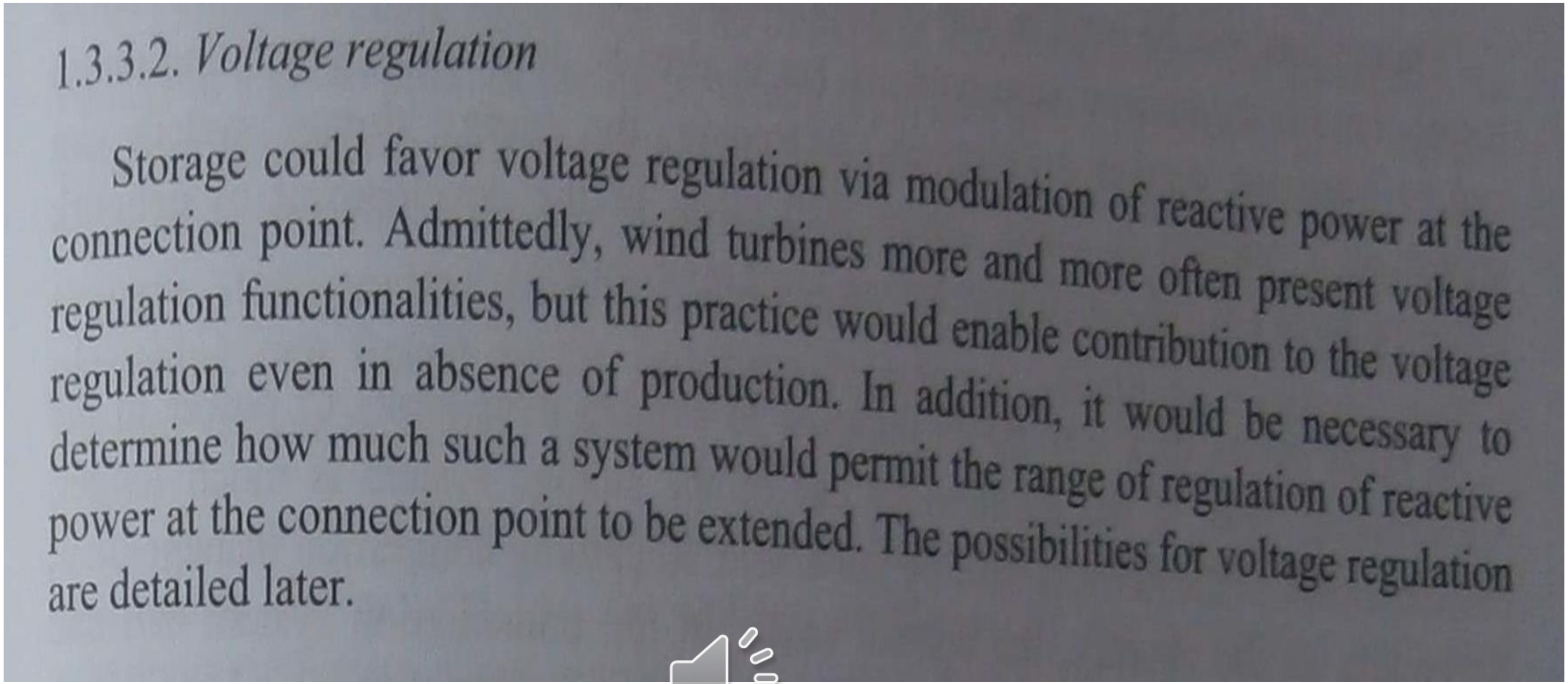
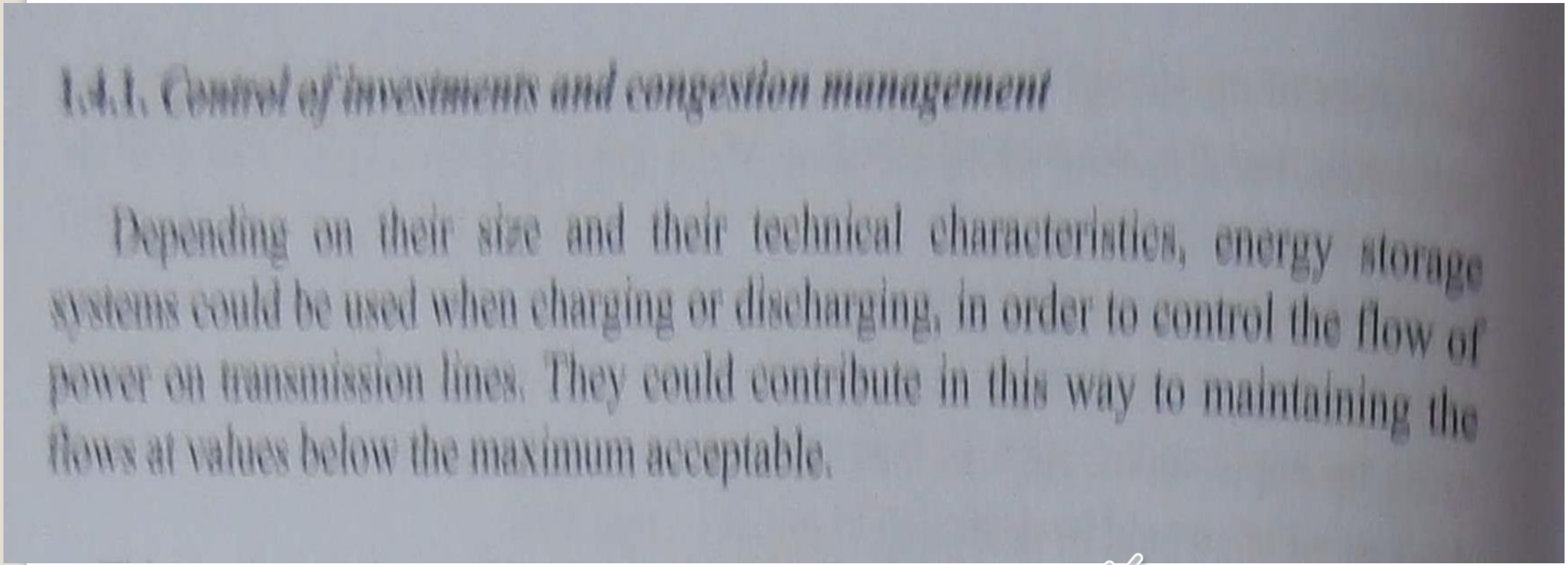


Figure 1.4. *Level of storage charge. At A, the charge is maximal; it is no longer possible to curtail production, whatever the power reserve available. Conversely, at B, it is no longer possible to increase production, no matter how much power reserve is available*



1.3.3.2. *Voltage regulation*

Storage could favor voltage regulation via modulation of reactive power at the connection point. Admittedly, wind turbines more and more often present voltage regulation functionalities, but this practice would enable contribution to the voltage regulation even in absence of production. In addition, it would be necessary to determine how much such a system would permit the range of regulation of reactive power at the connection point to be extended. The possibilities for voltage regulation are detailed later.



1.4.1. *Control of investments and congestion management*

Depending on their size and their technical characteristics, energy storage systems could be used when charging or discharging, in order to control the flow of power on transmission lines. They could contribute in this way to maintaining the flows at values below the maximum acceptable.

ENERGY STORAGE IN DISTRIBUTION NETWORKS

- Emergency power
- Load smoothing

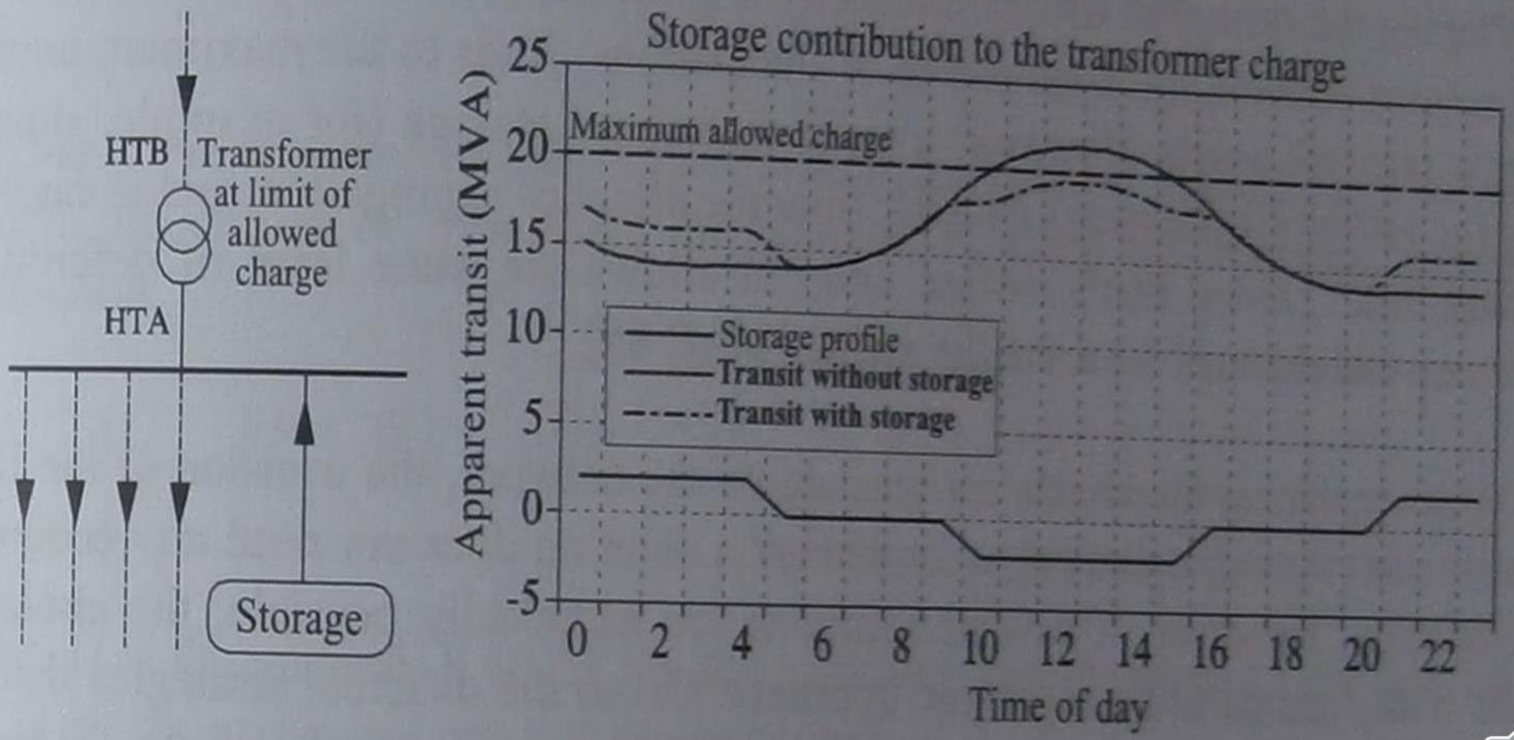
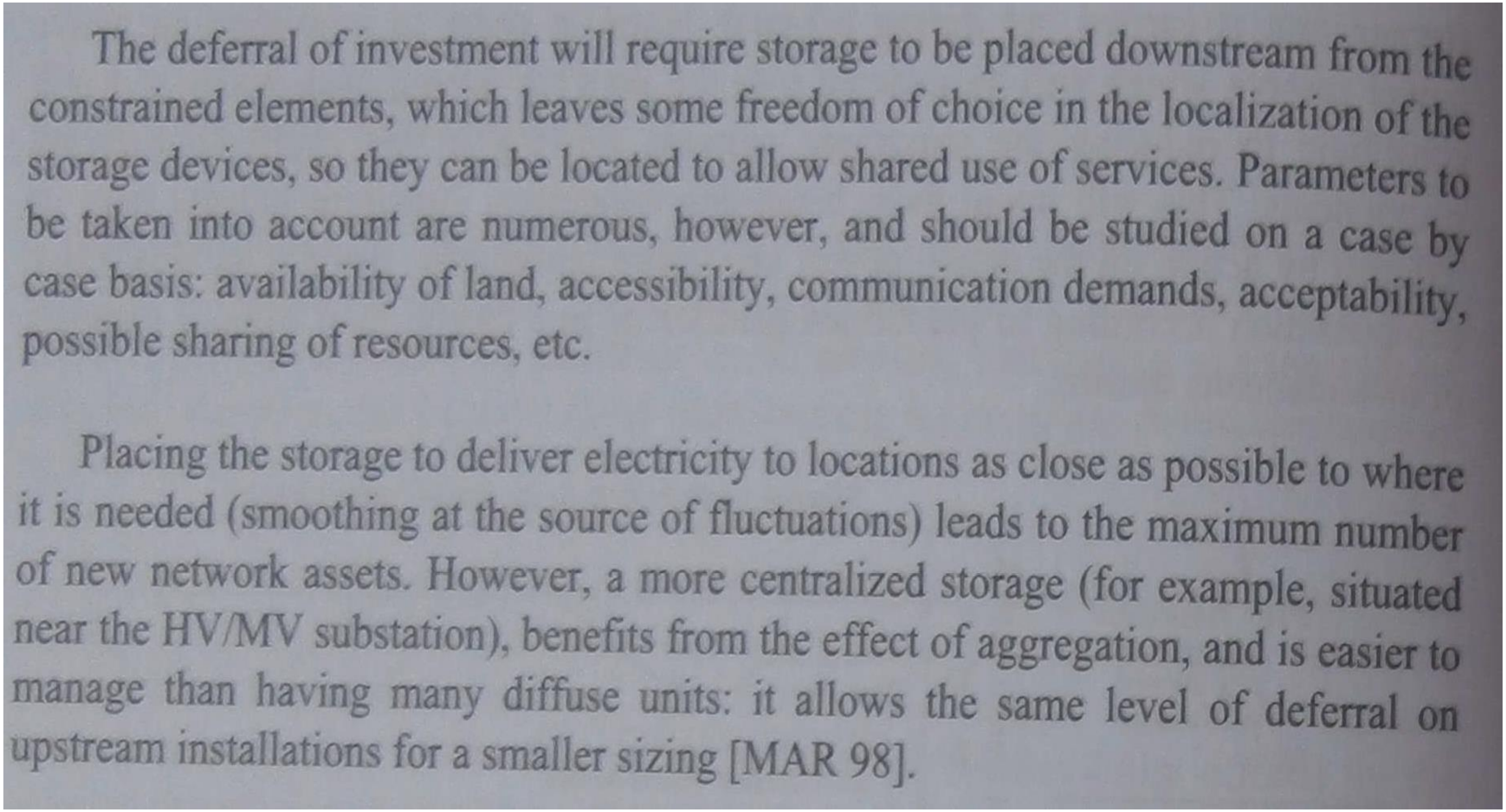


Figure 1.5. *An illustration of storage for load smoothing*



The deferral of investment will require storage to be placed downstream from the constrained elements, which leaves some freedom of choice in the localization of the storage devices, so they can be located to allow shared use of services. Parameters to be taken into account are numerous, however, and should be studied on a case by case basis: availability of land, accessibility, communication demands, acceptability, possible sharing of resources, etc.

Placing the storage to deliver electricity to locations as close as possible to where it is needed (smoothing at the source of fluctuations) leads to the maximum number of new network assets. However, a more centralized storage (for example, situated near the HV/MV substation), benefits from the effect of aggregation, and is easier to manage than having many diffuse units: it allows the same level of deferral on upstream installations for a smaller sizing [MAR 98].

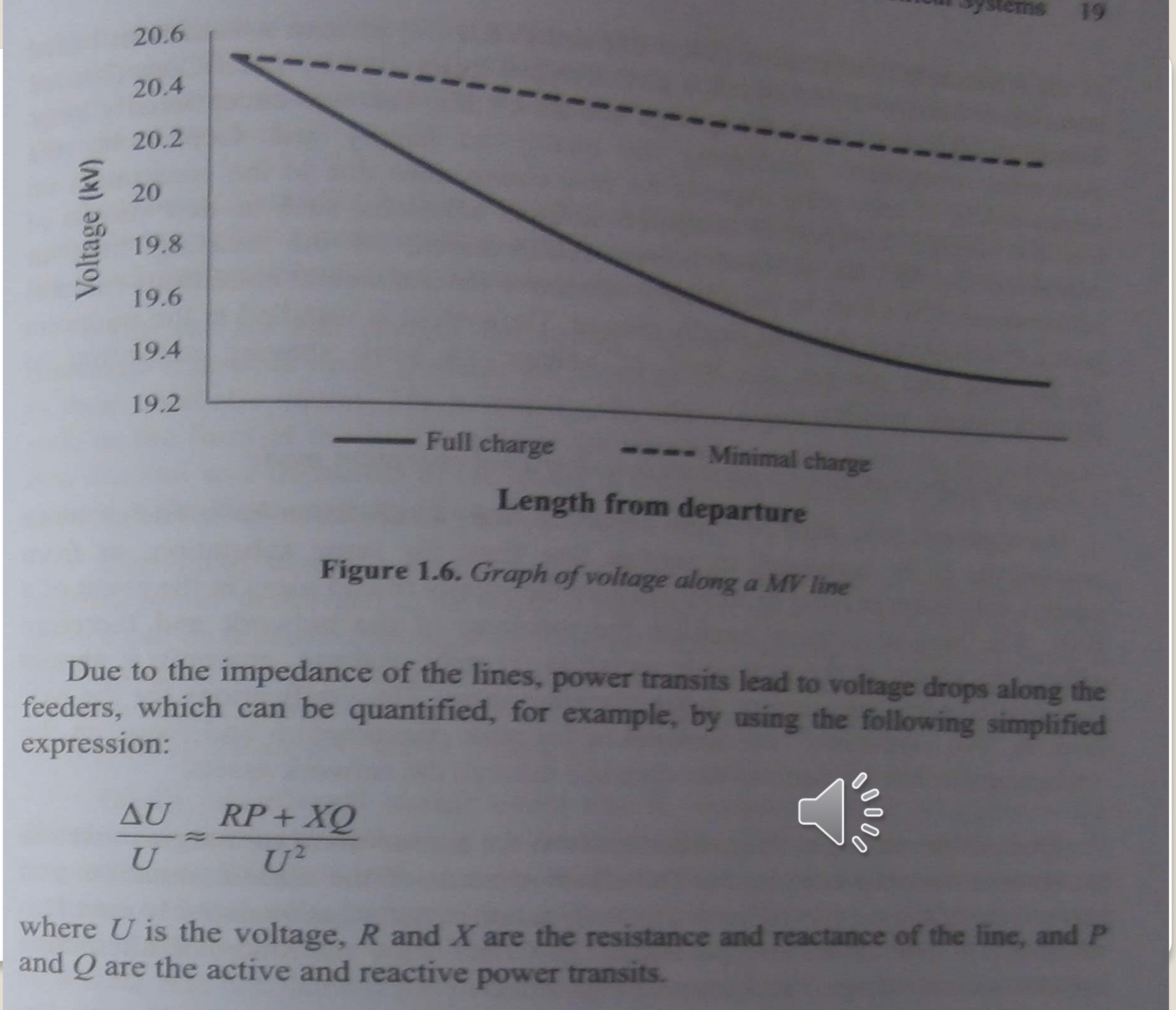
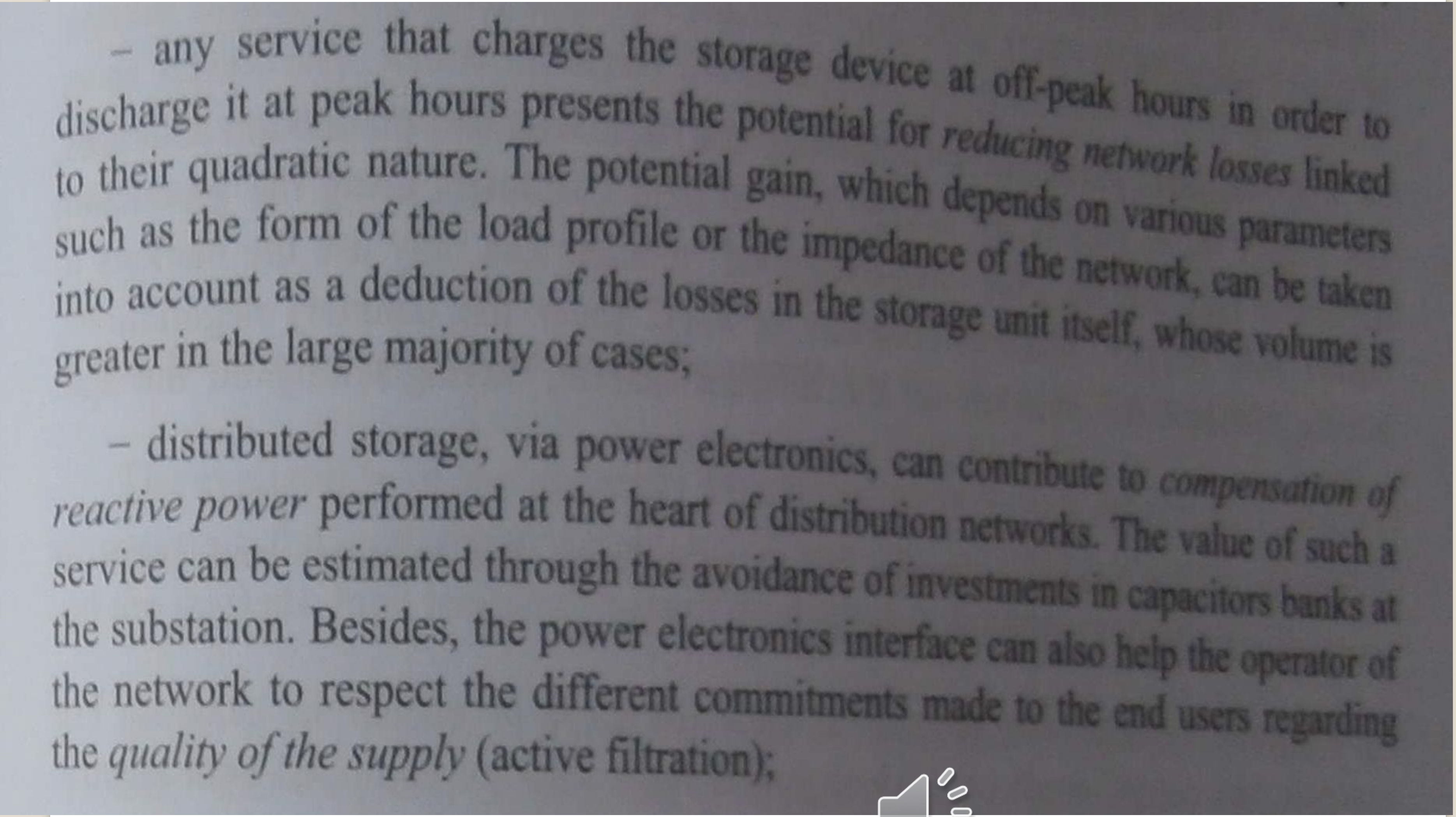


Figure 1.6. *Graph of voltage along a MV line*

Due to the impedance of the lines, power transits lead to voltage drops along the feeders, which can be quantified, for example, by using the following simplified expression:

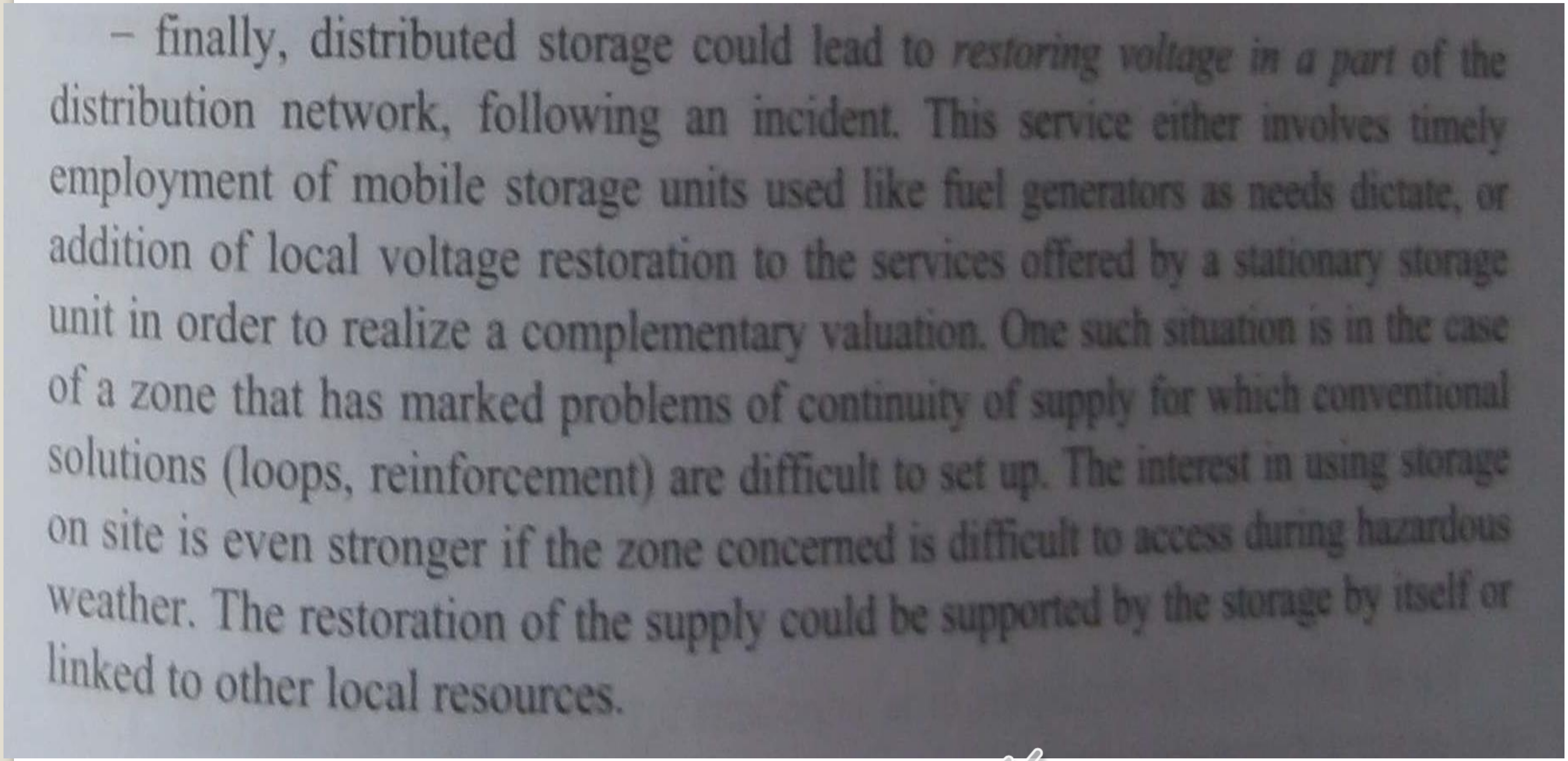
$$\frac{\Delta U}{U} \approx \frac{RP + XQ}{U^2}$$

where U is the voltage, R and X are the resistance and reactance of the line, and P and Q are the active and reactive power transits.



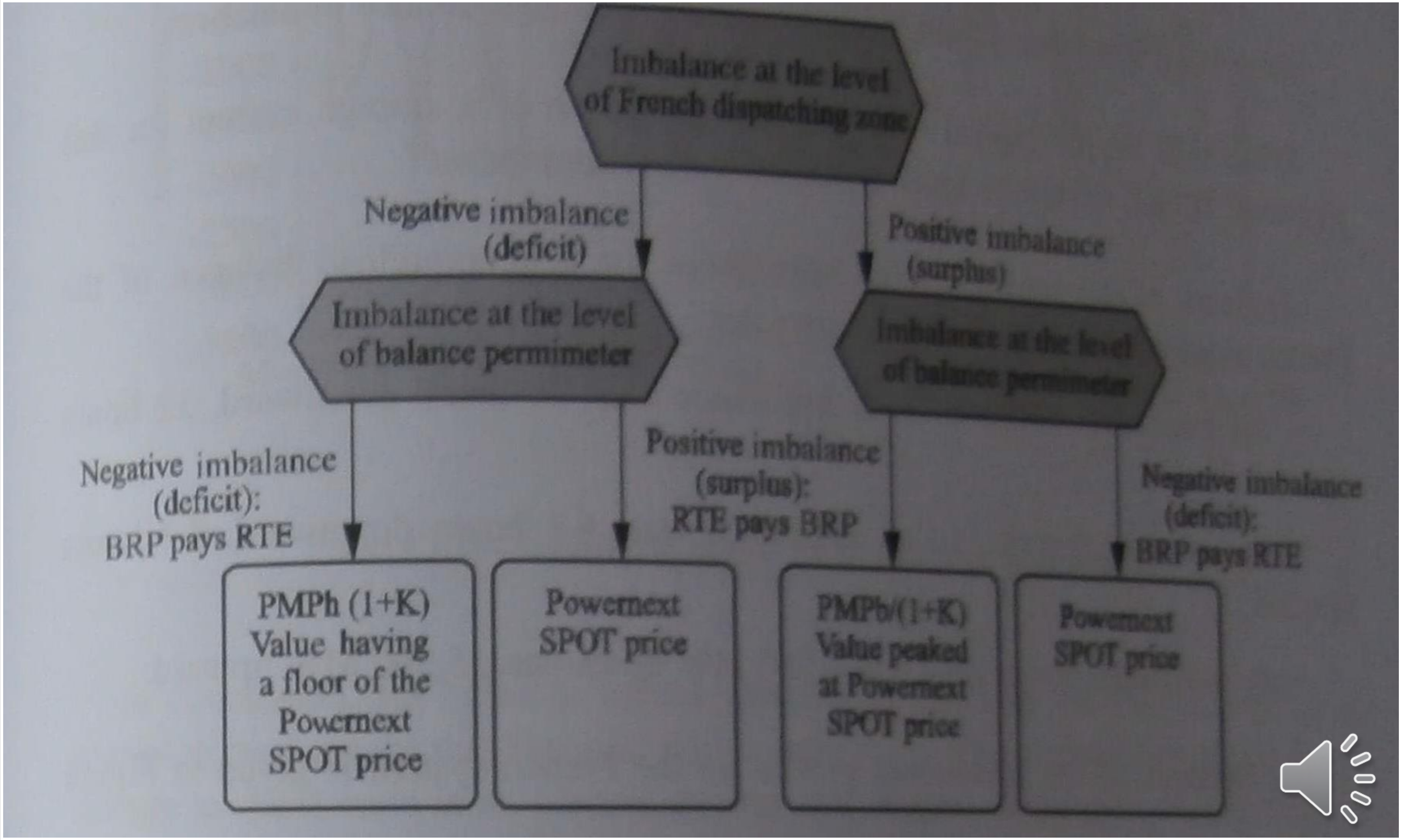
– any service that charges the storage device at off-peak hours in order to discharge it at peak hours presents the potential for *reducing network losses* linked to their quadratic nature. The potential gain, which depends on various parameters such as the form of the load profile or the impedance of the network, can be taken into account as a deduction of the losses in the storage unit itself, whose volume is greater in the large majority of cases;

– distributed storage, via power electronics, can contribute to *compensation of reactive power* performed at the heart of distribution networks. The value of such a service can be estimated through the avoidance of investments in capacitors banks at the substation. Besides, the power electronics interface can also help the operator of the network to respect the different commitments made to the end users regarding the *quality of the supply* (active filtration);



– finally, distributed storage could lead to *restoring voltage in a part* of the distribution network, following an incident. This service either involves timely employment of mobile storage units used like fuel generators as needs dictate, or addition of local voltage restoration to the services offered by a stationary storage unit in order to realize a complementary valuation. One such situation is in the case of a zone that has marked problems of continuity of supply for which conventional solutions (loops, reinforcement) are difficult to set up. The interest in using storage on site is even stronger if the zone concerned is difficult to access during hazardous weather. The restoration of the supply could be supported by the storage by itself or linked to other local resources.

- Energy Storage for retailers
- Energy storage to secure the cost of sourcing
- Energy storage for consumers
- Energy storage for quality & continuity of supply


Imbalance at the level of French dispatching zone
Negative imbalance (deficit)
Positive imbalance (surplus)
Imbalance at the level of balance permimeter
Imbalance at the level of balance permimeter
Negative imbalance (deficit): BRP pays RTE
Positive imbalance (surplus): RTE pays BRP
Negative imbalance (deficit): BRP pays RTE
PMPh (1+K) Value having a floor of the Powernext SPOT price
Powernext SPOT price
PMPh/(1+K) Value peaked at Powernext SPOT price
Powernext SPOT price

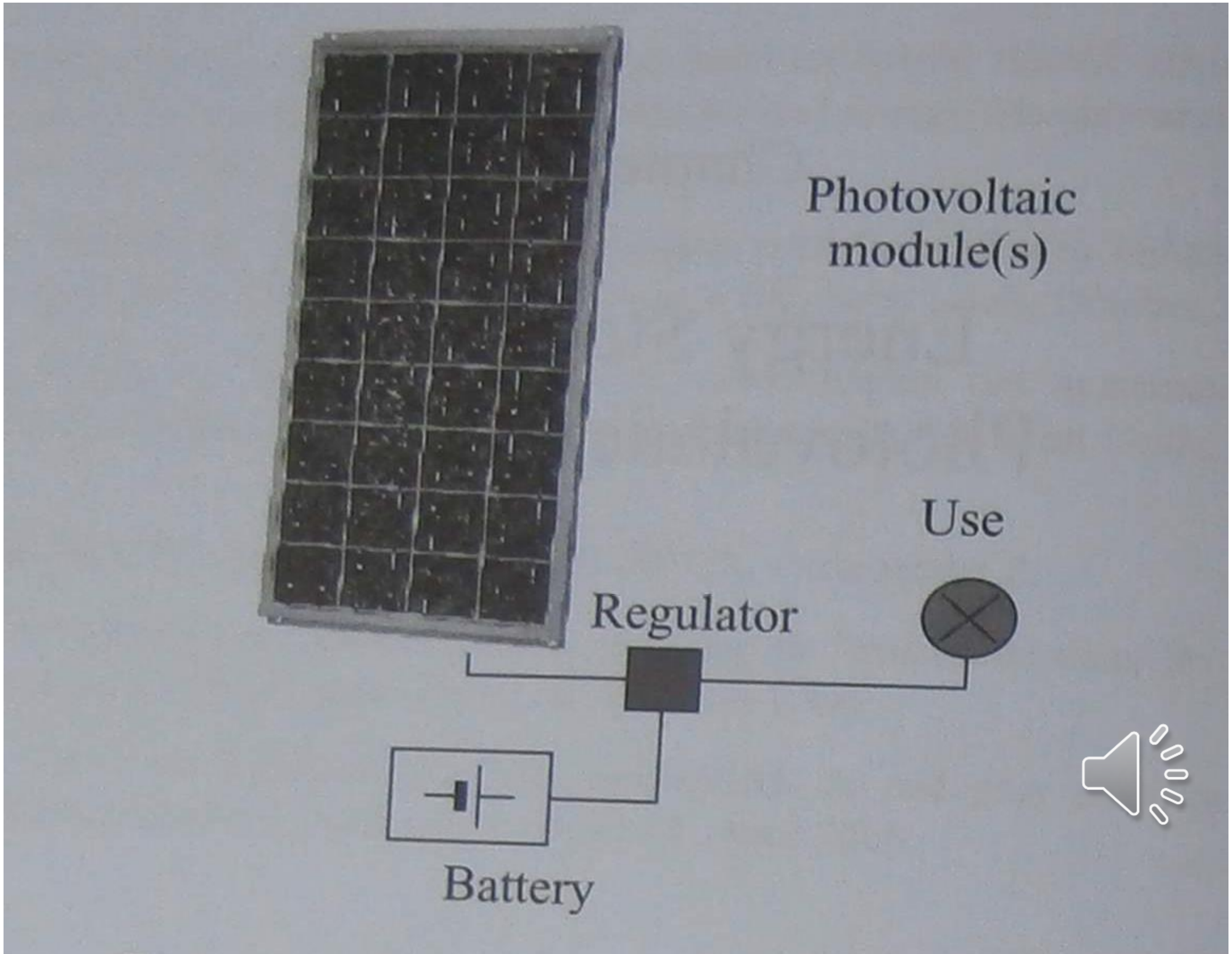


Figure 3.1. *Diagram of a stand alone photovoltaic system*

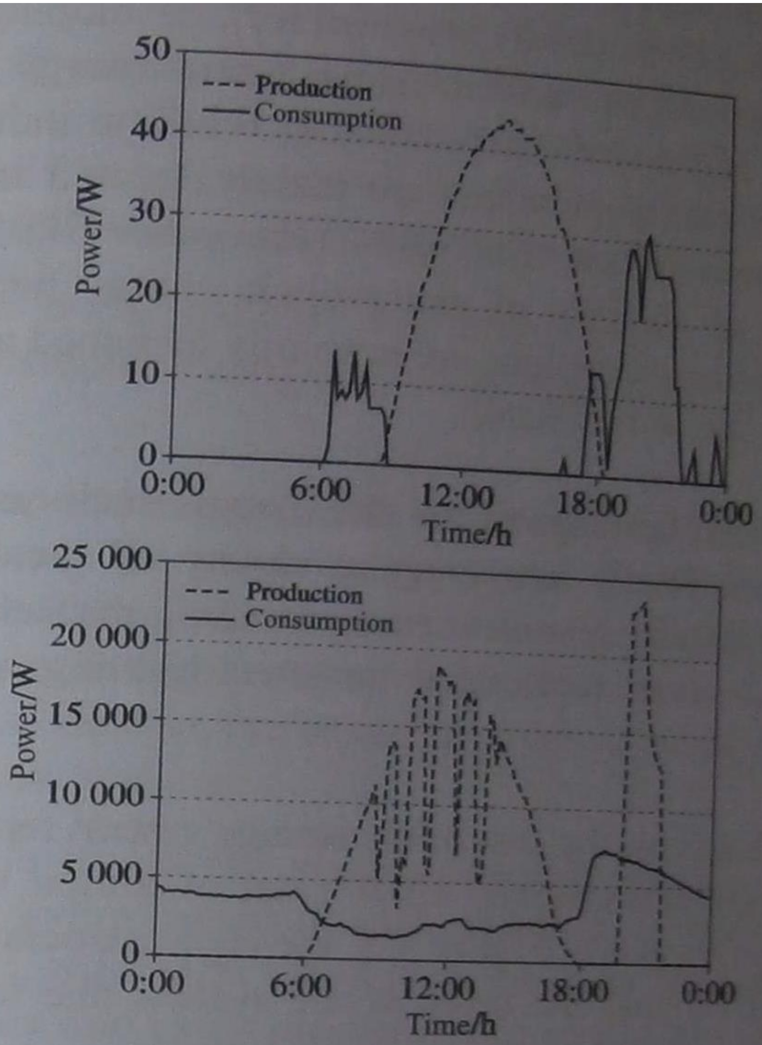
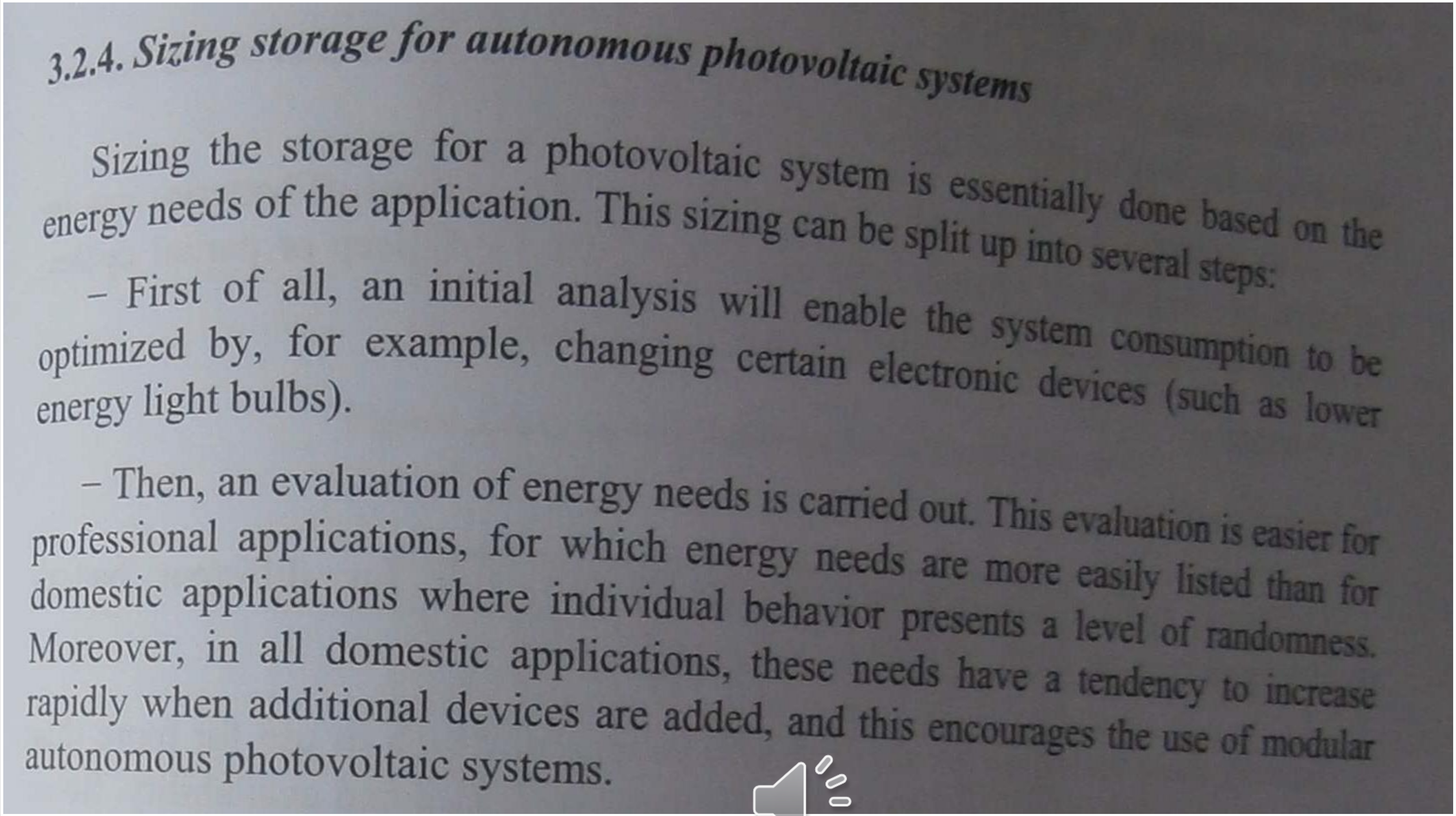


Figure 3.2. *Two examples of energy production and consumption over 1 day for two stand alone systems: lighting kit (above) and hybrid system with photovoltaic panels coupled with a diesel generator (below)*

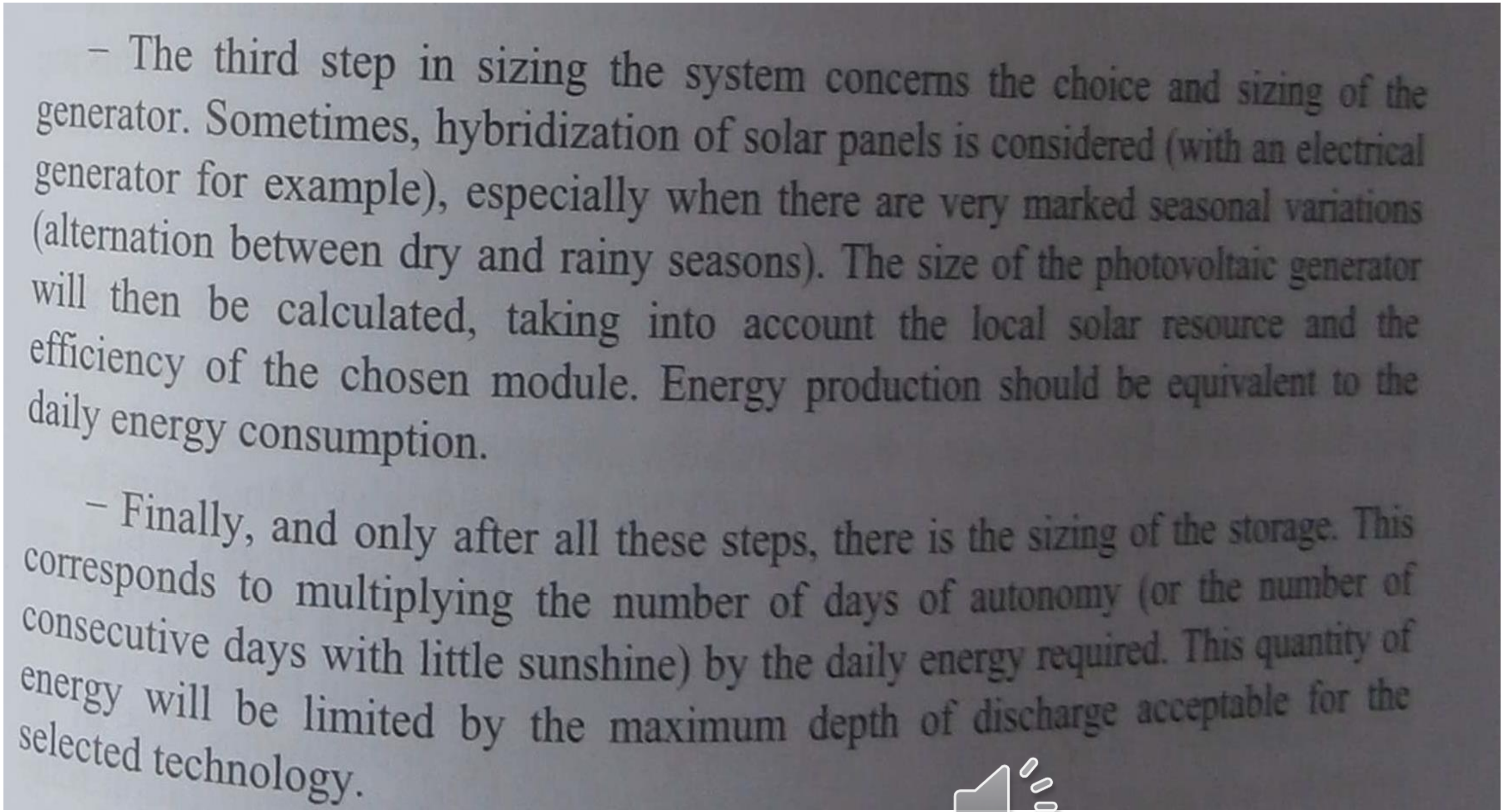


3.2.4. *Sizing storage for autonomous photovoltaic systems*

Sizing the storage for a photovoltaic system is essentially done based on the energy needs of the application. This sizing can be split up into several steps:

– First of all, an initial analysis will enable the system consumption to be optimized by, for example, changing certain electronic devices (such as lower energy light bulbs).

– Then, an evaluation of energy needs is carried out. This evaluation is easier for professional applications, for which energy needs are more easily listed than for domestic applications where individual behavior presents a level of randomness. Moreover, in all domestic applications, these needs have a tendency to increase rapidly when additional devices are added, and this encourages the use of modular autonomous photovoltaic systems.



– The third step in sizing the system concerns the choice and sizing of the generator. Sometimes, hybridization of solar panels is considered (with an electrical generator for example), especially when there are very marked seasonal variations (alternation between dry and rainy seasons). The size of the photovoltaic generator will then be calculated, taking into account the local solar resource and the efficiency of the chosen module. Energy production should be equivalent to the daily energy consumption.

– Finally, and only after all these steps, there is the sizing of the storage. This corresponds to multiplying the number of days of autonomy (or the number of consecutive days with little sunshine) by the daily energy required. This quantity of energy will be limited by the maximum depth of discharge acceptable for the selected technology.

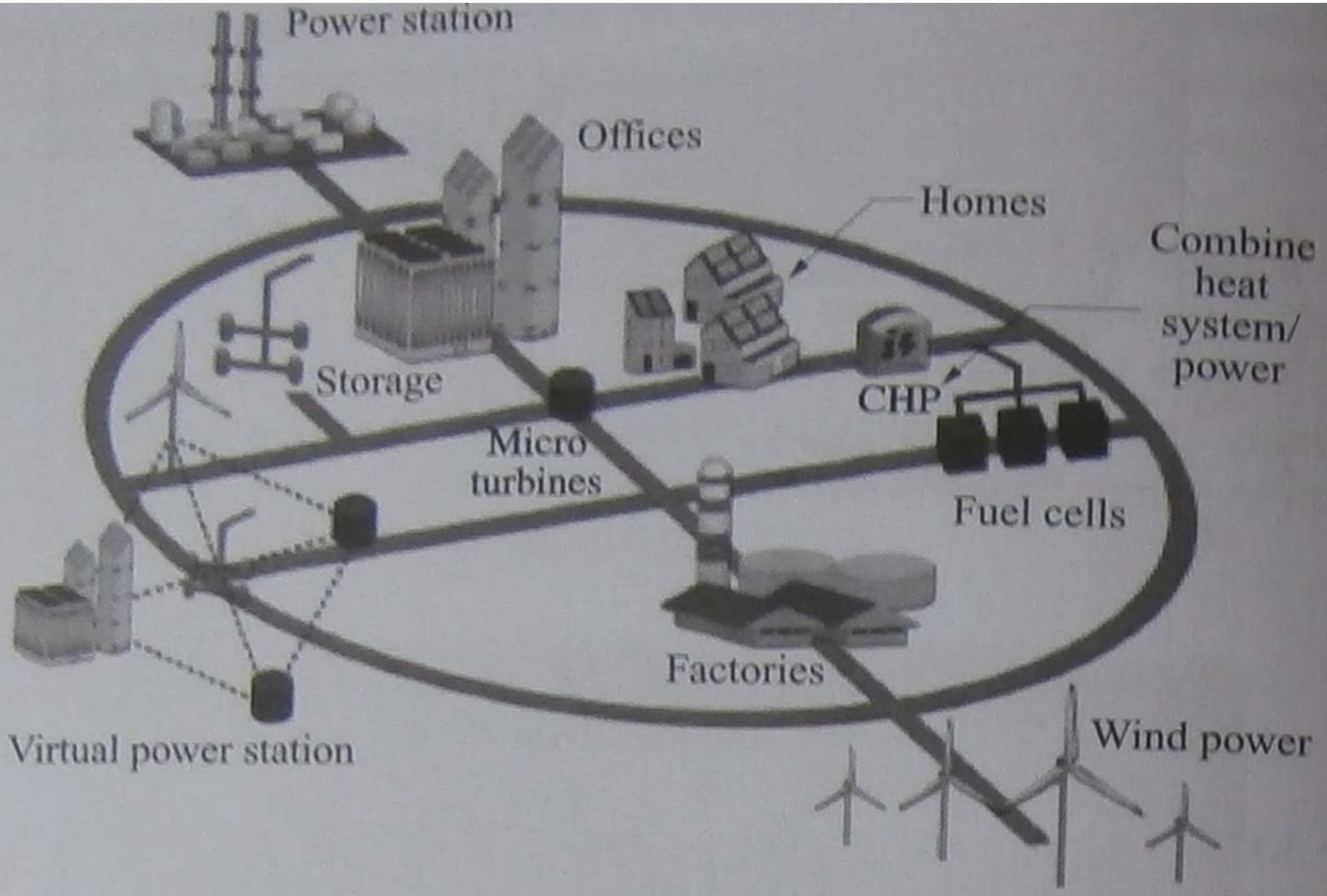
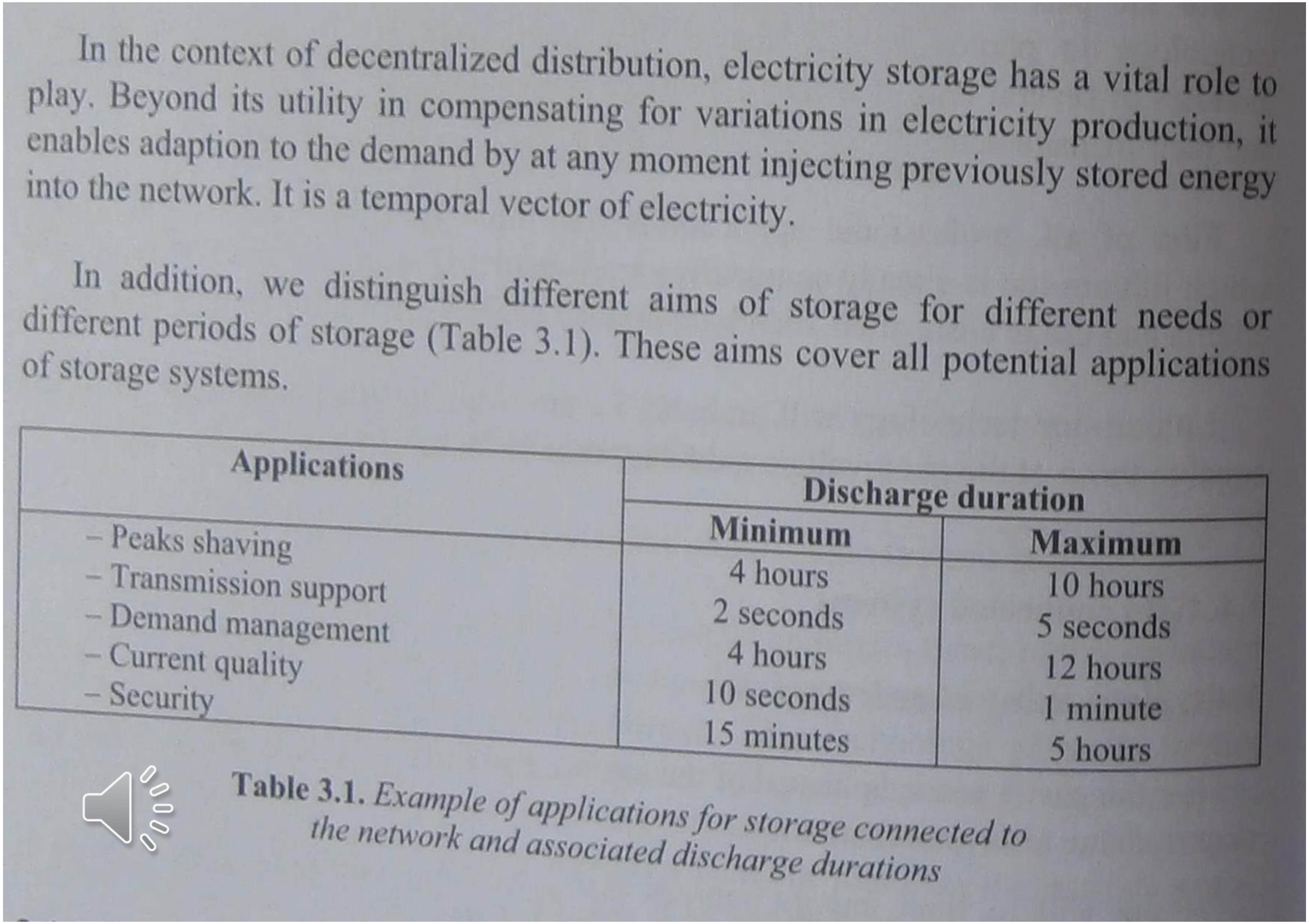


Figure 3.14. *Configuration of the electric network showing decentralized production sources*



In the context of decentralized distribution, electricity storage has a vital role to play. Beyond its utility in compensating for variations in electricity production, it enables adaption to the demand by at any moment injecting previously stored energy into the network. It is a temporal vector of electricity.

In addition, we distinguish different aims of storage for different needs or different periods of storage (Table 3.1). These aims cover all potential applications of storage systems.

Applications	**Discharge duration**	
	Minimum	**Maximum**
– Peaks shaving	4 hours	10 hours
– Transmission support	2 seconds	5 seconds
– Demand management	4 hours	12 hours
– Current quality	10 seconds	1 minute
– Security	15 minutes	5 hours

Table 3.1. *Example of applications for storage connected to the network and associated discharge durations*

Figure 3.17. *Electrolyte redox batteries*

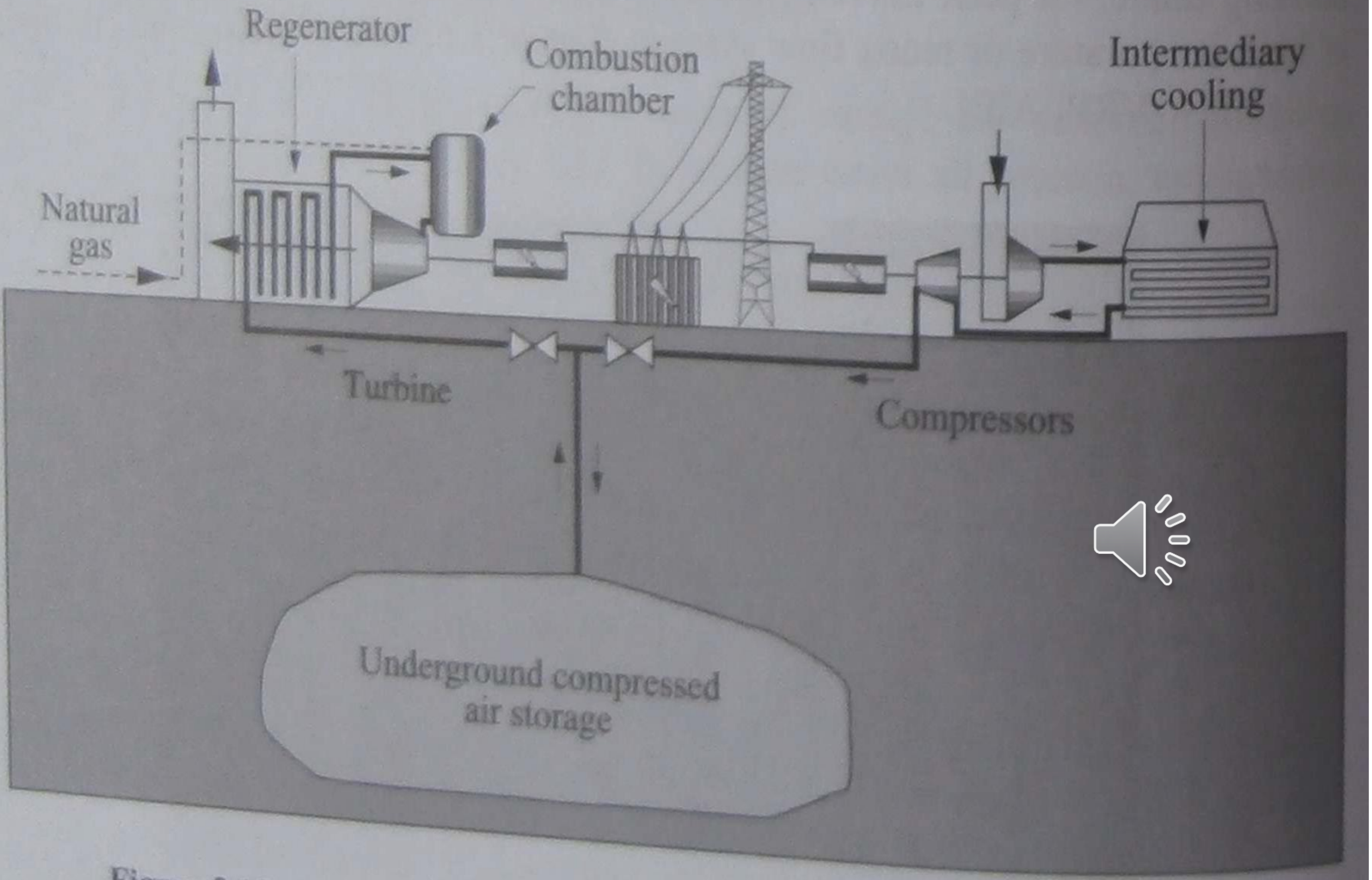
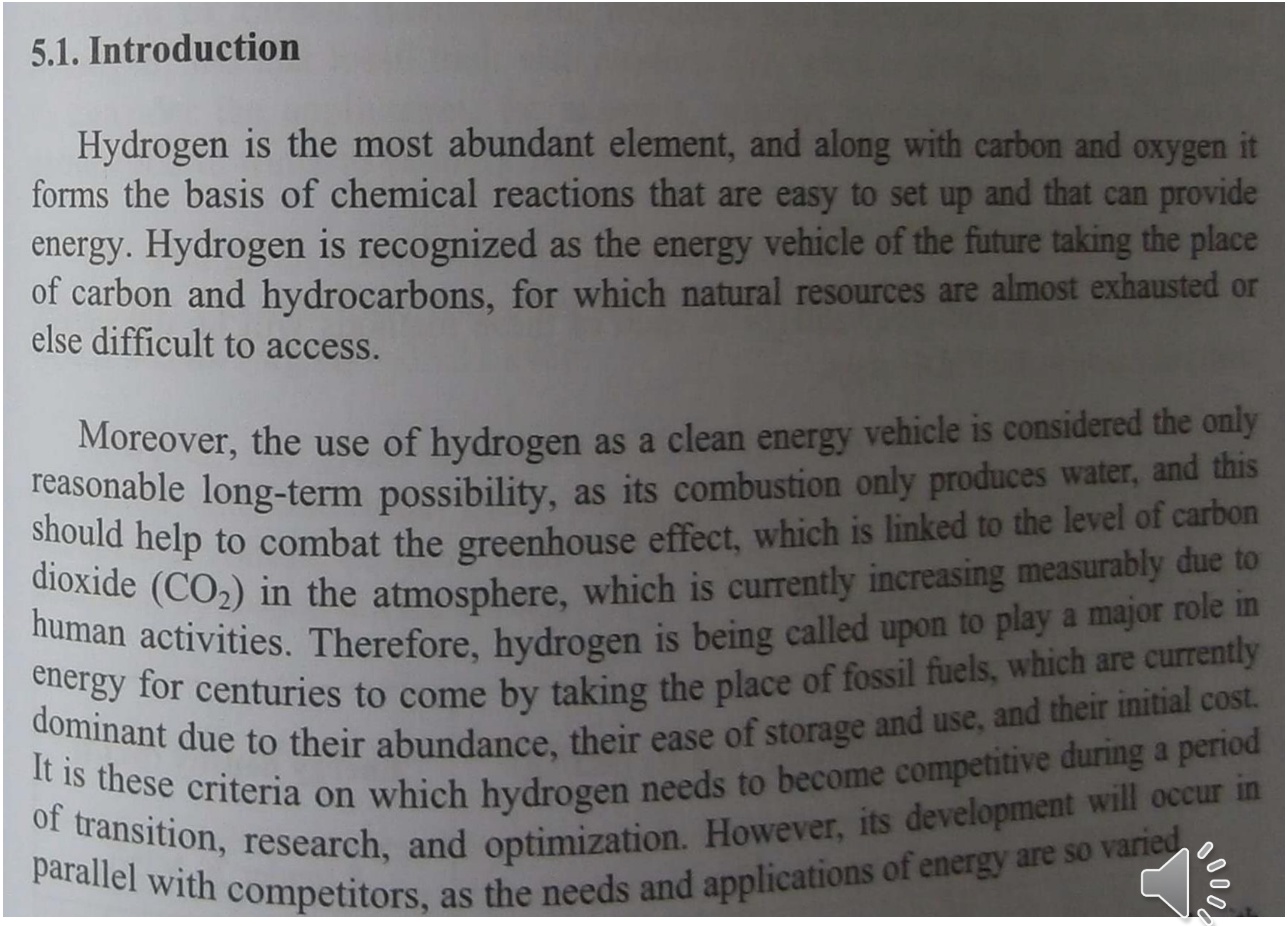


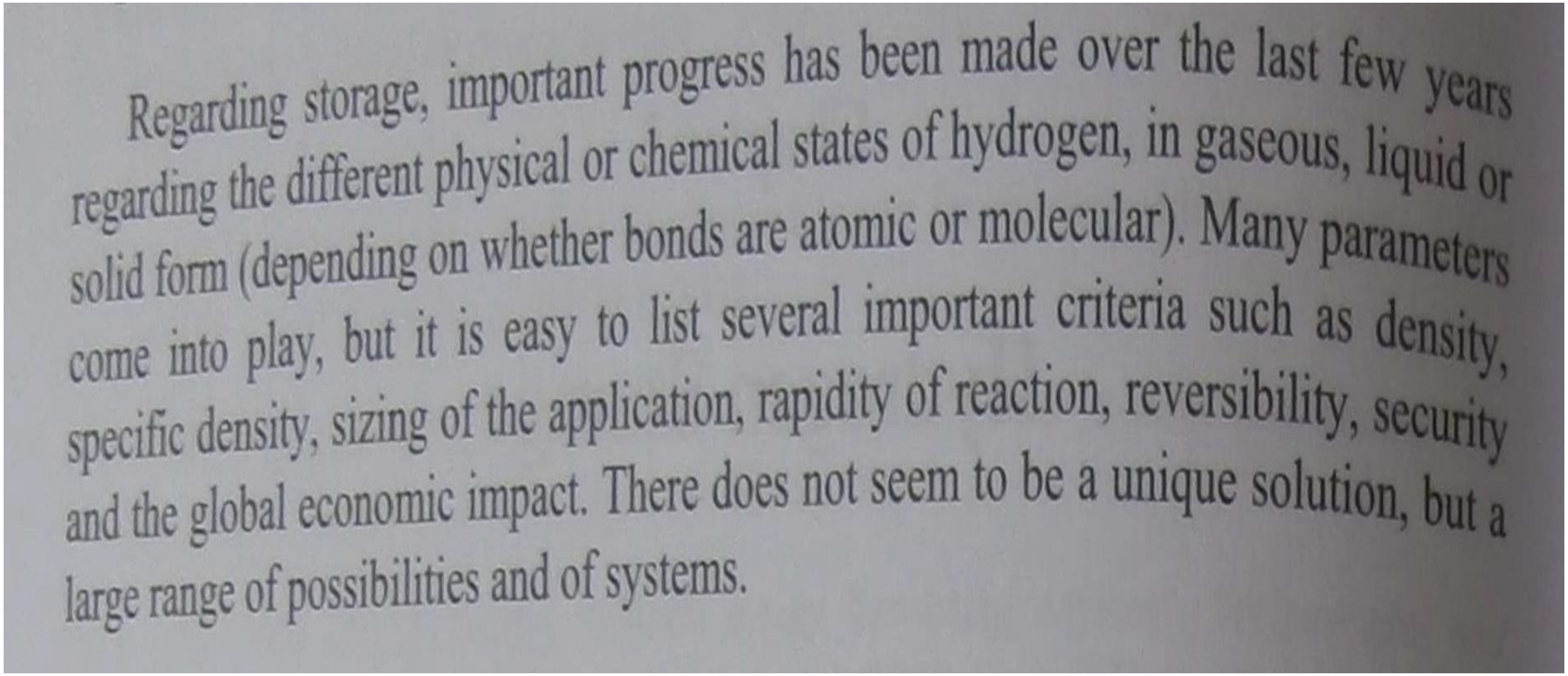
Figure 3.18. *Cavern equipped with air compressors coupled with gas turbines*



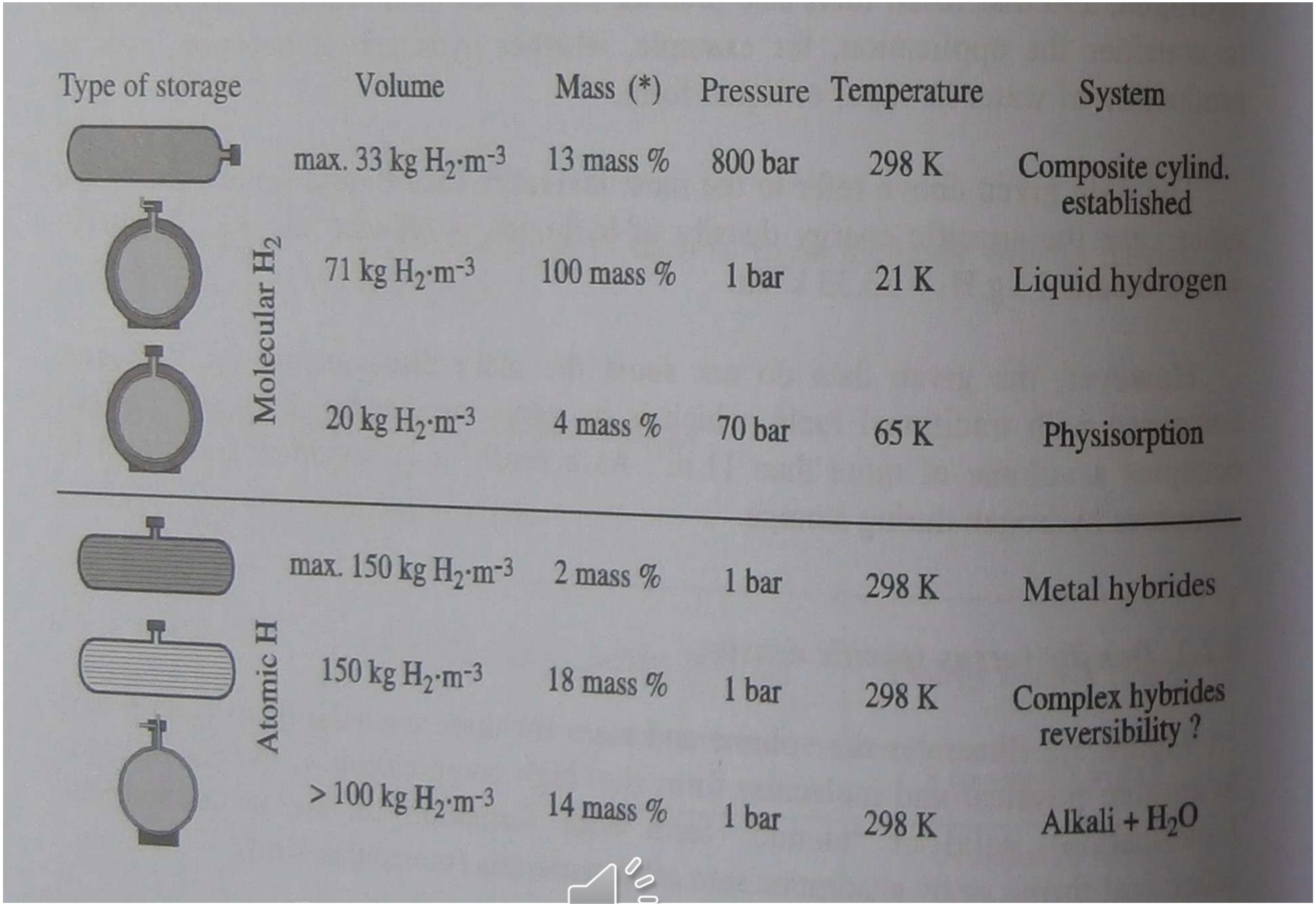
5.1. Introduction

Hydrogen is the most abundant element, and along with carbon and oxygen it forms the basis of chemical reactions that are easy to set up and that can provide energy. Hydrogen is recognized as the energy vehicle of the future taking the place of carbon and hydrocarbons, for which natural resources are almost exhausted or else difficult to access.

Moreover, the use of hydrogen as a clean energy vehicle is considered the only reasonable long-term possibility, as its combustion only produces water, and this should help to combat the greenhouse effect, which is linked to the level of carbon dioxide (CO_2) in the atmosphere, which is currently increasing measurably due to human activities. Therefore, hydrogen is being called upon to play a major role in energy for centuries to come by taking the place of fossil fuels, which are currently dominant due to their abundance, their ease of storage and use, and their initial cost. It is these criteria on which hydrogen needs to become competitive during a period of transition, research, and optimization. However, its development will occur in parallel with competitors, as the needs and applications of energy are so varied

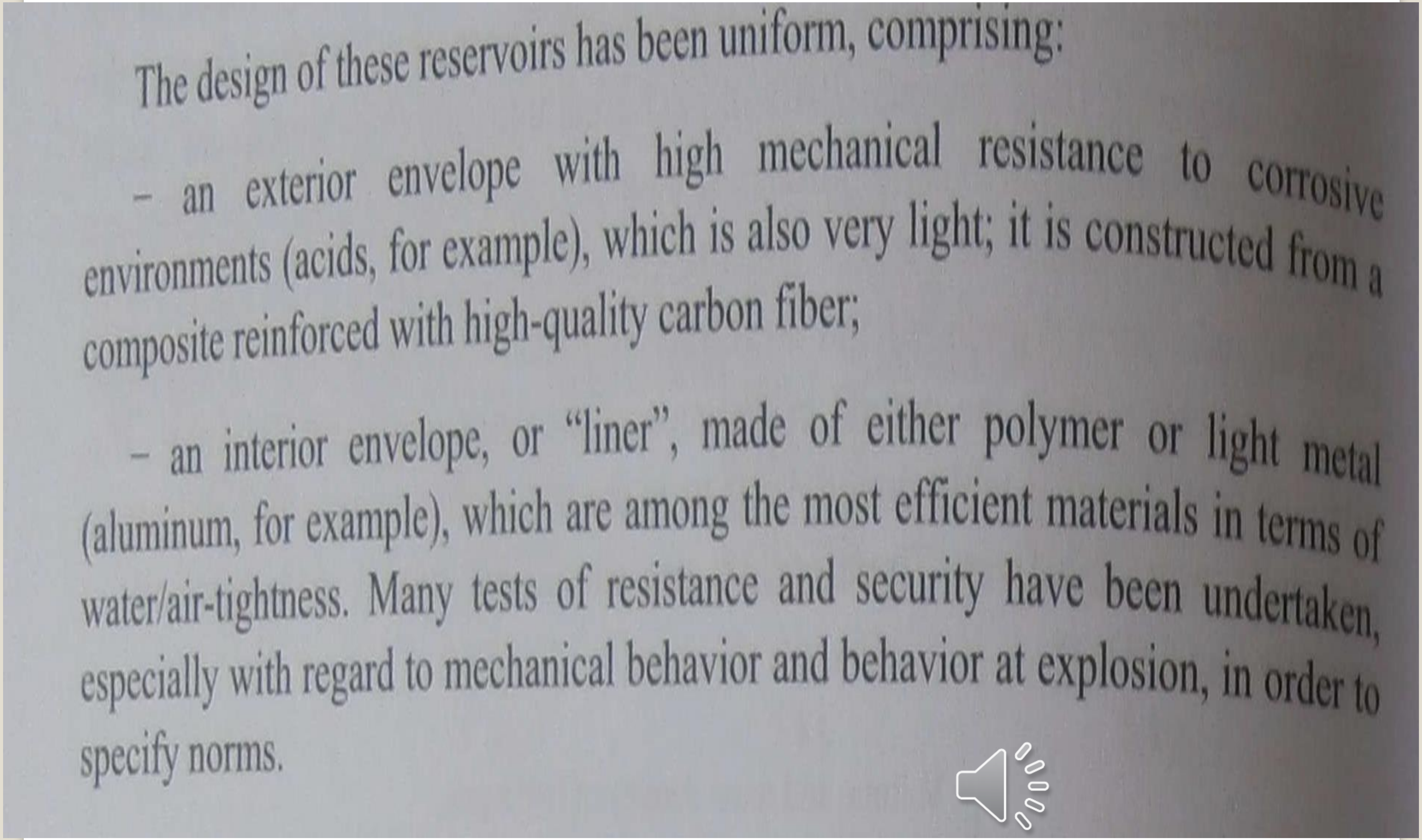


Regarding storage, important progress has been made over the last few years regarding the different physical or chemical states of hydrogen, in gaseous, liquid or solid form (depending on whether bonds are atomic or molecular). Many parameters come into play, but it is easy to list several important criteria such as density, specific density, sizing of the application, rapidity of reaction, reversibility, security and the global economic impact. There does not seem to be a unique solution, but a large range of possibilities and of systems.



Type of storage	Volume	Mass (*)	Pressure	Temperature	System
Molecular H_2	max. 33 kg $H_2 \cdot m^{-3}$	13 mass %	800 bar	298 K	Composite cylind. established
	71 kg $H_2 \cdot m^{-3}$	100 mass %	1 bar	21 K	Liquid hydrogen
	20 kg $H_2 \cdot m^{-3}$	4 mass %	70 bar	65 K	Physisorption
Atomic H	max. 150 kg $H_2 \cdot m^{-3}$	2 mass %	1 bar	298 K	Metal hybrides
	150 kg $H_2 \cdot m^{-3}$	18 mass %	1 bar	298 K	Complex hybrides reversibility ?
	> 100 kg $H_2 \cdot m^{-3}$	14 mass %	1 bar	298 K	Alkali + H_2O

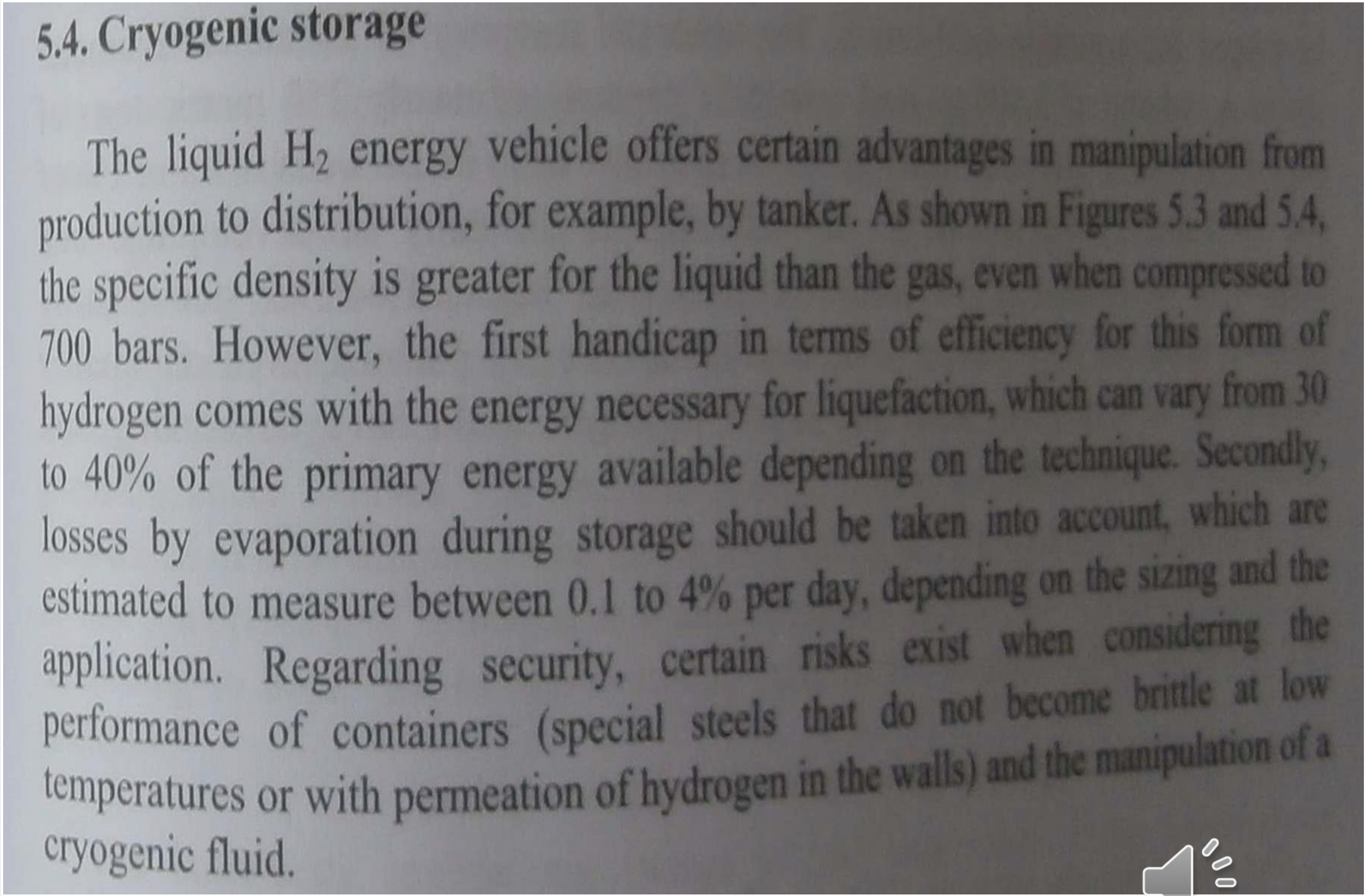
Pressurised Hydrogen Storage



The design of these reservoirs has been uniform, comprising:

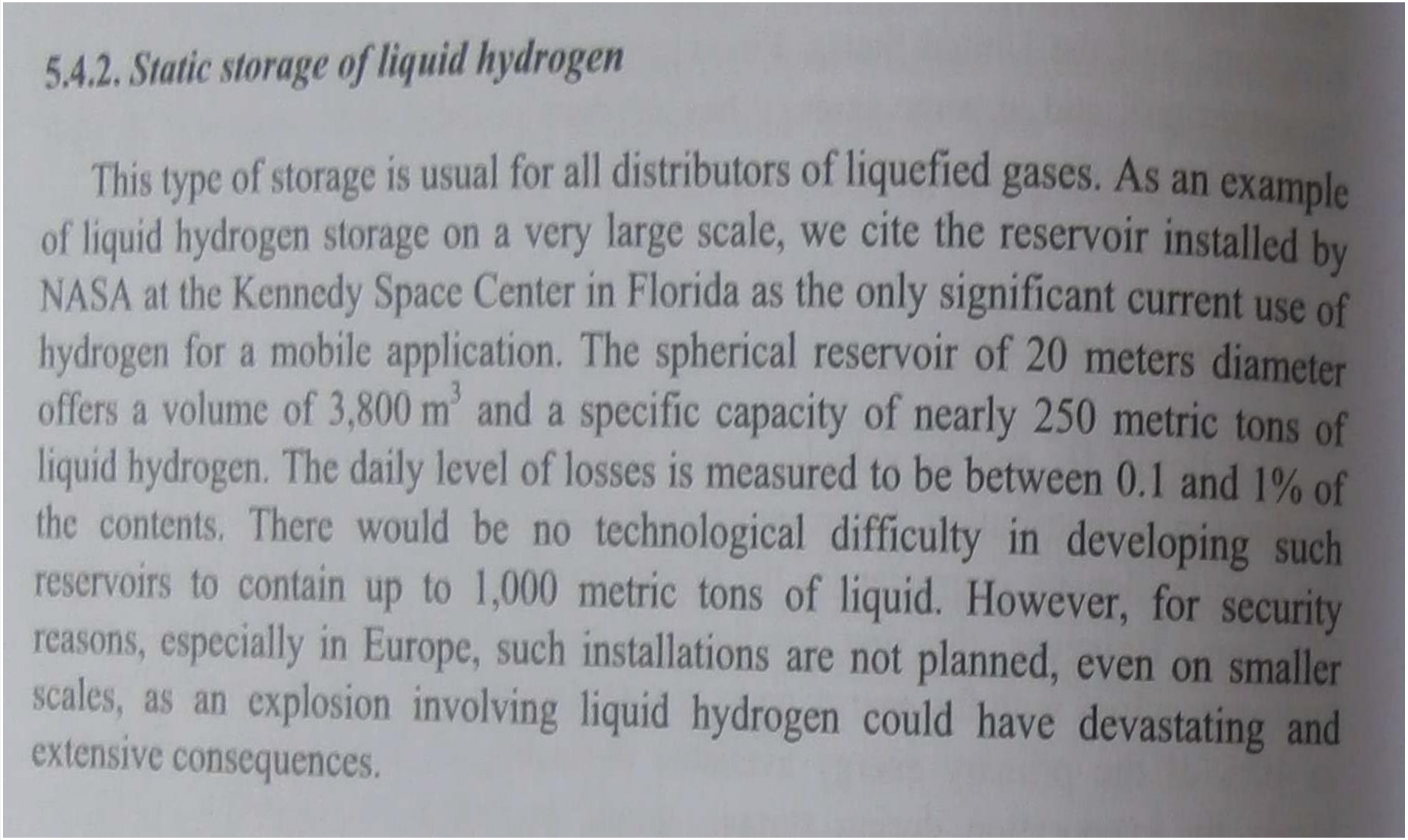
– an exterior envelope with high mechanical resistance to corrosive environments (acids, for example), which is also very light; it is constructed from a composite reinforced with high-quality carbon fiber;

– an interior envelope, or “liner”, made of either polymer or light metal (aluminum, for example), which are among the most efficient materials in terms of water/air-tightness. Many tests of resistance and security have been undertaken, especially with regard to mechanical behavior and behavior at explosion, in order to specify norms.



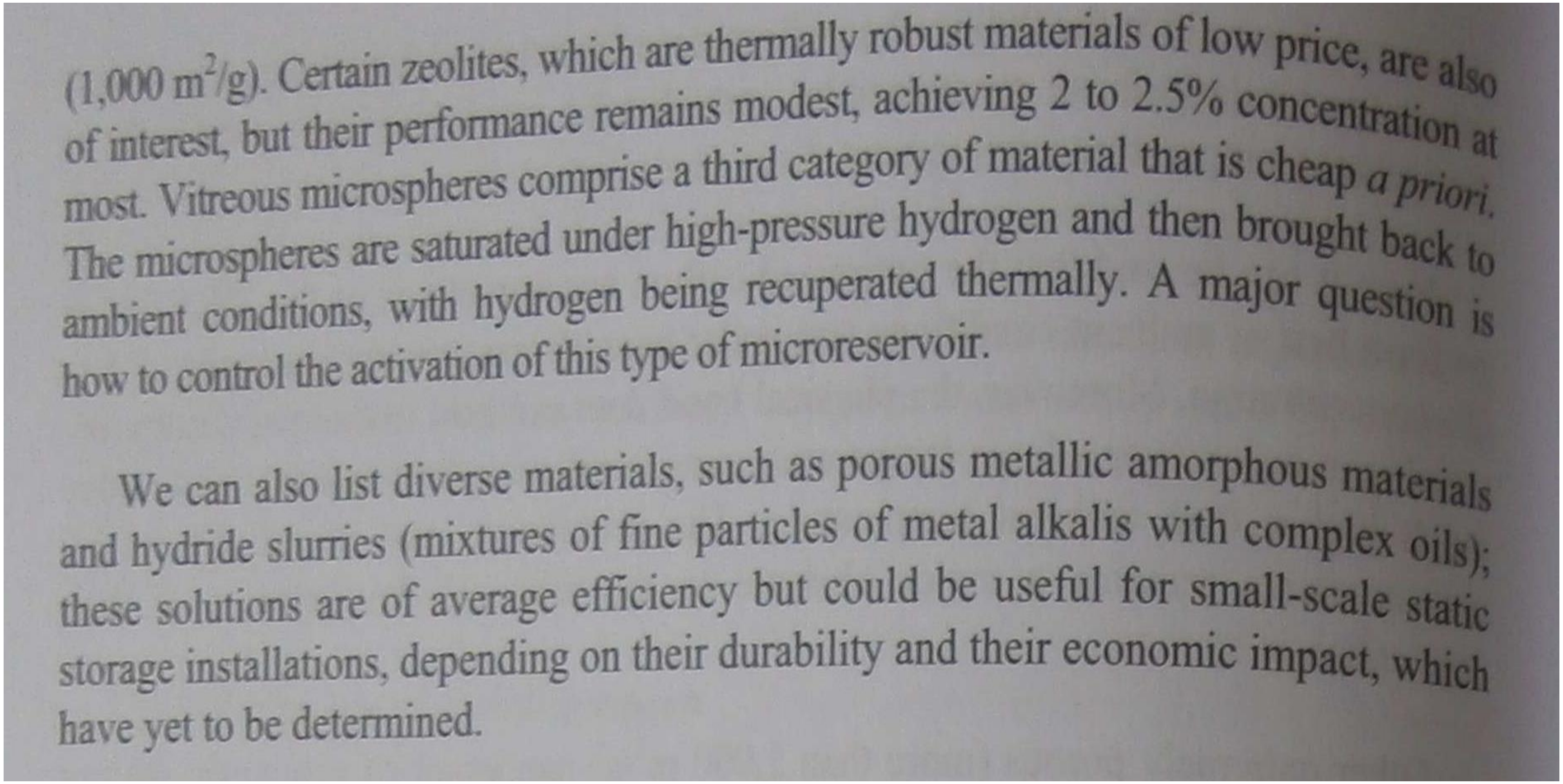
5.4. Cryogenic storage

The liquid H_2 energy vehicle offers certain advantages in manipulation from production to distribution, for example, by tanker. As shown in Figures 5.3 and 5.4, the specific density is greater for the liquid than the gas, even when compressed to 700 bars. However, the first handicap in terms of efficiency for this form of hydrogen comes with the energy necessary for liquefaction, which can vary from 30 to 40% of the primary energy available depending on the technique. Secondly, losses by evaporation during storage should be taken into account, which are estimated to measure between 0.1 to 4% per day, depending on the sizing and the application. Regarding security, certain risks exist when considering the performance of containers (special steels that do not become brittle at low temperatures or with permeation of hydrogen in the walls) and the manipulation of a cryogenic fluid.



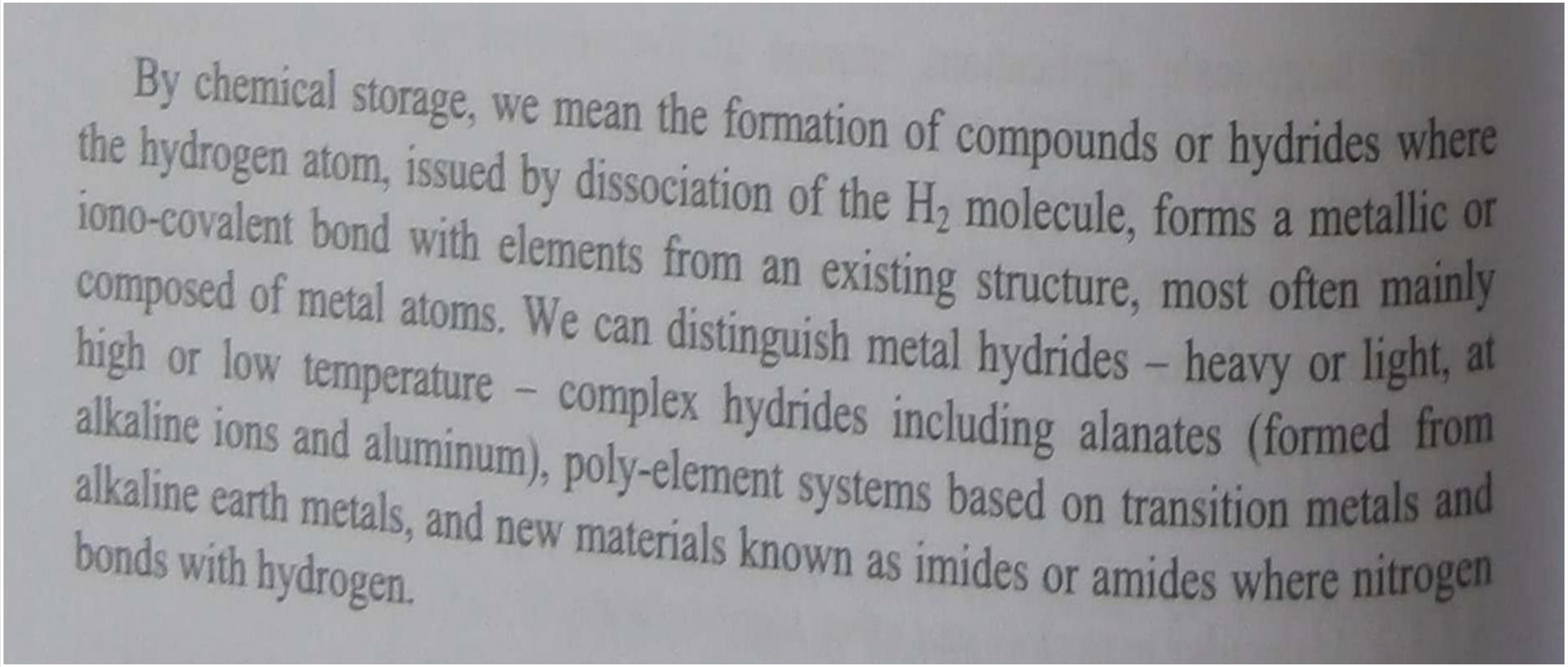
5.4.2. *Static storage of liquid hydrogen*

This type of storage is usual for all distributors of liquefied gases. As an example of liquid hydrogen storage on a very large scale, we cite the reservoir installed by NASA at the Kennedy Space Center in Florida as the only significant current use of hydrogen for a mobile application. The spherical reservoir of 20 meters diameter offers a volume of 3,800 m^3 and a specific capacity of nearly 250 metric tons of liquid hydrogen. The daily level of losses is measured to be between 0.1 and 1% of the contents. There would be no technological difficulty in developing such reservoirs to contain up to 1,000 metric tons of liquid. However, for security reasons, especially in Europe, such installations are not planned, even on smaller scales, as an explosion involving liquid hydrogen could have devastating and extensive consequences.



(1,000 m^2/g). Certain zeolites, which are thermally robust materials of low price, are also of interest, but their performance remains modest, achieving 2 to 2.5% concentration at most. Vitreous microspheres comprise a third category of material that is cheap *a priori*. The microspheres are saturated under high-pressure hydrogen and then brought back to ambient conditions, with hydrogen being recuperated thermally. A major question is how to control the activation of this type of microreservoir.

We can also list diverse materials, such as porous metallic amorphous materials and hydride slurries (mixtures of fine particles of metal alkalis with complex oils); these solutions are of average efficiency but could be useful for small-scale static storage installations, depending on their durability and their economic impact, which have yet to be determined.



By chemical storage, we mean the formation of compounds or hydrides where the hydrogen atom, issued by dissociation of the H_2 molecule, forms a metallic or iono-covalent bond with elements from an existing structure, most often mainly composed of metal atoms. We can distinguish metal hydrides – heavy or light, at high or low temperature – complex hydrides including alanates (formed from alkaline ions and aluminum), poly-element systems based on transition metals and alkaline earth metals, and new materials known as imides or amides where nitrogen bonds with hydrogen.

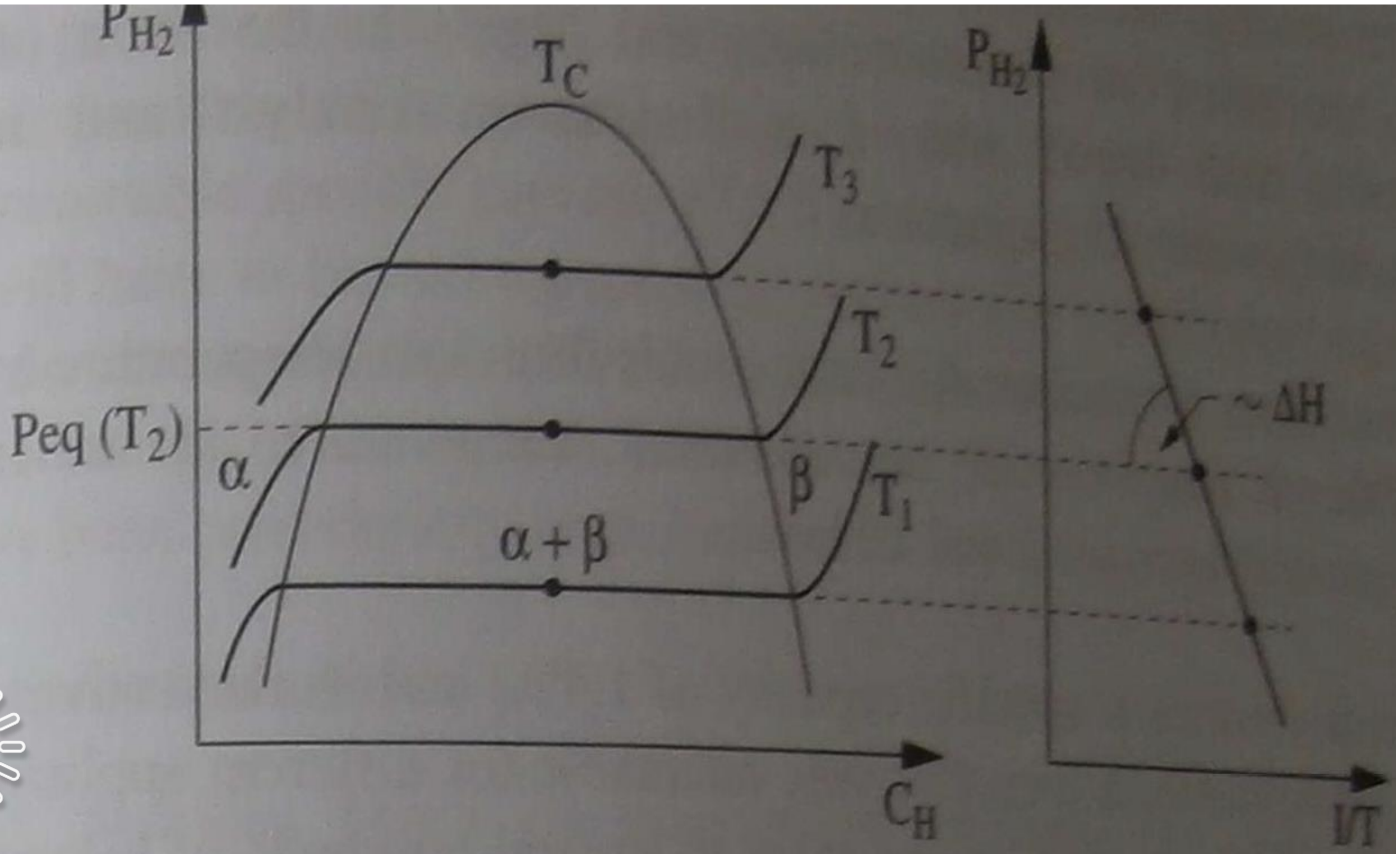
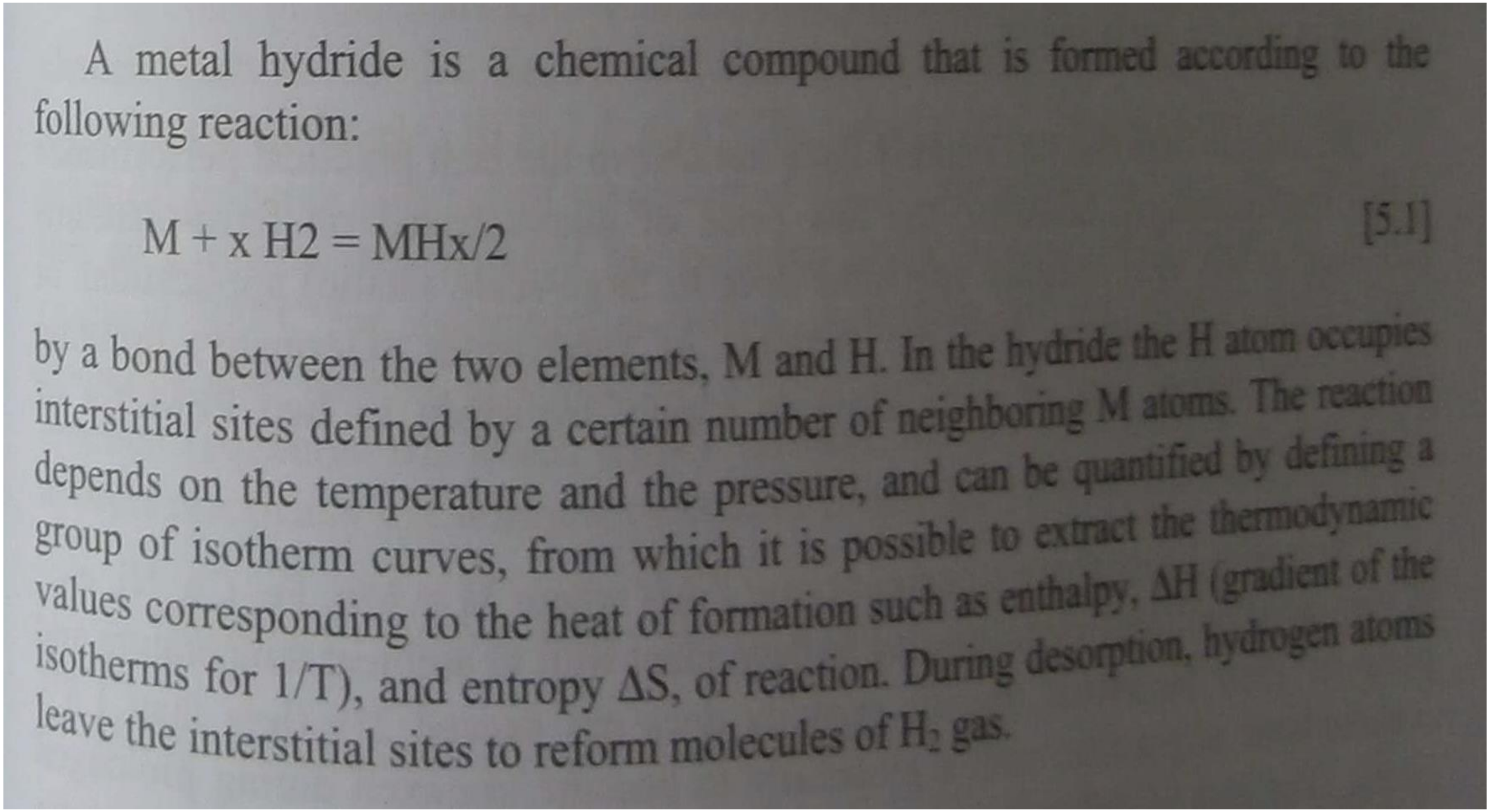


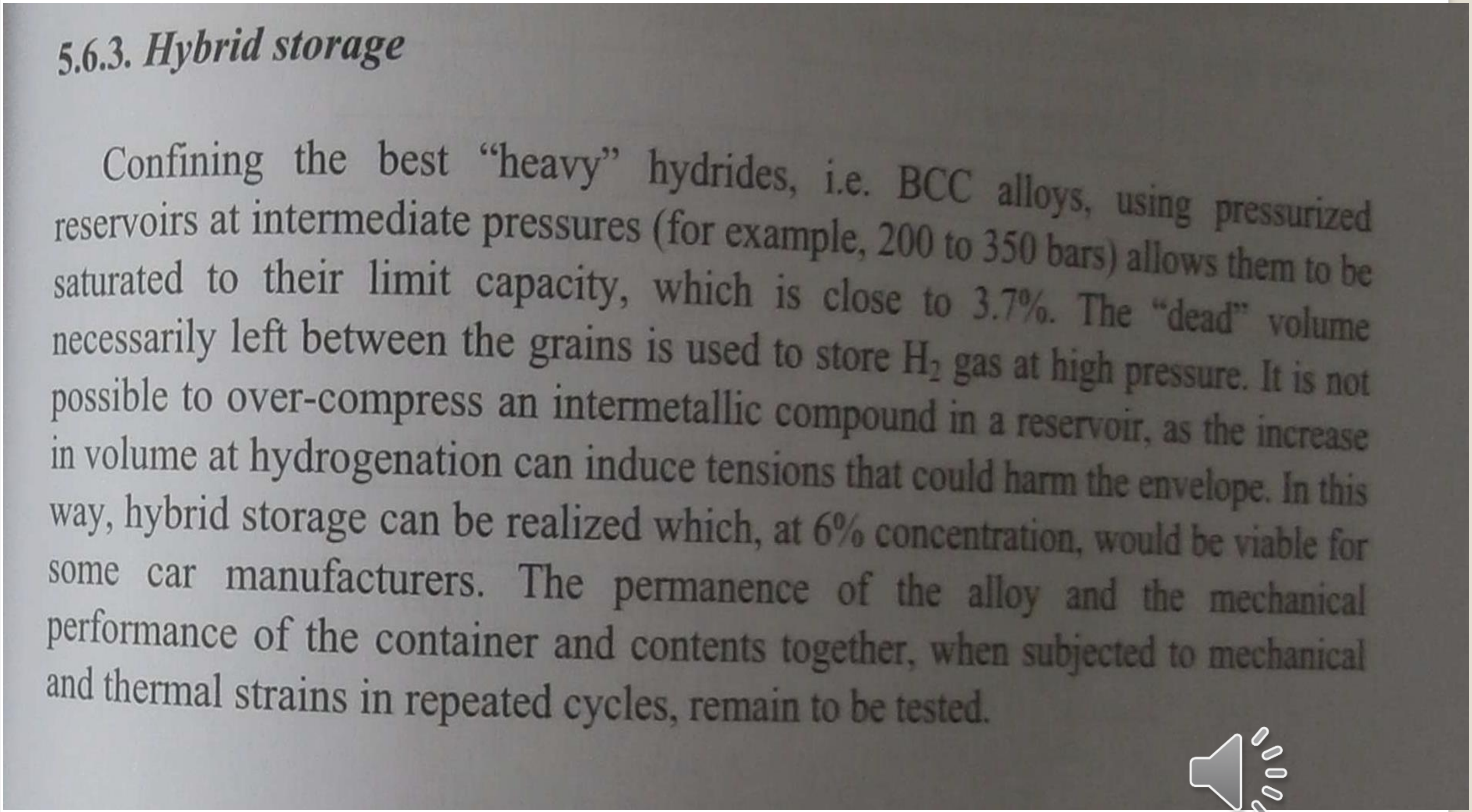
Figure 5.5. *Left: phase diagram for metal/hydrogen, relating the concentration C_H to the pressure of H_2 for different temperatures. Right: analysis of the equilibrium plateau "solid solution (α) – hydride (β)" in 1/T determining the enthalpy of formation of the hydride (Van't Hoff's law)*



A metal hydride is a chemical compound that is formed according to the following reaction:

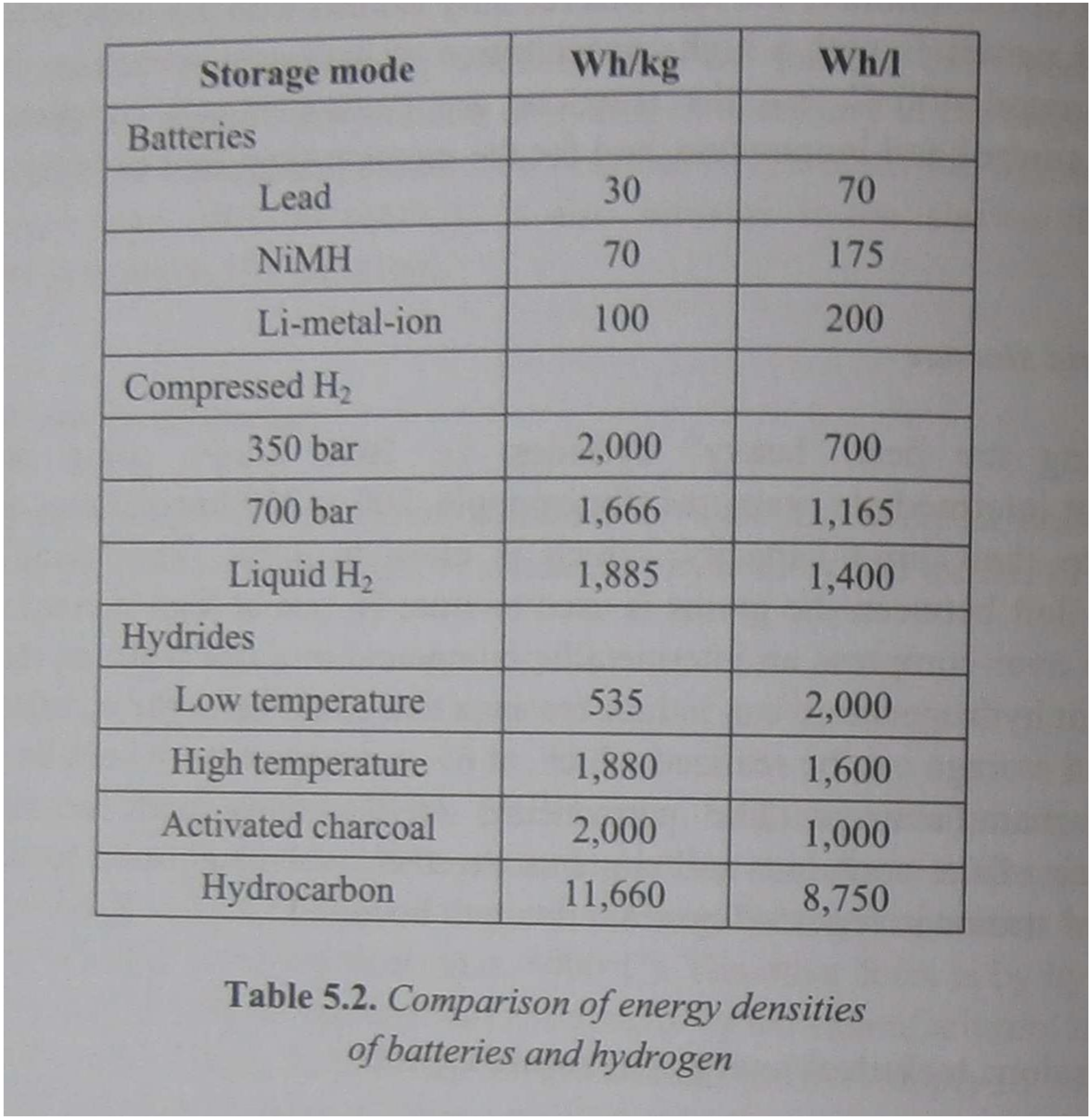
$$M + x\,H2 = MHx/2 \qquad [5.1]$$

by a bond between the two elements, M and H. In the hydride the H atom occupies interstitial sites defined by a certain number of neighboring M atoms. The reaction depends on the temperature and the pressure, and can be quantified by defining a group of isotherm curves, from which it is possible to extract the thermodynamic values corresponding to the heat of formation such as enthalpy, ΔH (gradient of the isotherms for 1/T), and entropy ΔS, of reaction. During desorption, hydrogen atoms leave the interstitial sites to reform molecules of H_2 gas.



5.6.3. *Hybrid storage*

Confining the best "heavy" hydrides, i.e. BCC alloys, using pressurized reservoirs at intermediate pressures (for example, 200 to 350 bars) allows them to be saturated to their limit capacity, which is close to 3.7%. The "dead" volume necessarily left between the grains is used to store H_2 gas at high pressure. It is not possible to over-compress an intermetallic compound in a reservoir, as the increase in volume at hydrogenation can induce tensions that could harm the envelope. In this way, hybrid storage can be realized which, at 6% concentration, would be viable for some car manufacturers. The permanence of the alloy and the mechanical performance of the container and contents together, when subjected to mechanical and thermal strains in repeated cycles, remain to be tested.



Storage mode	Wh/kg	Wh/l
Batteries		
Lead	30	70
NiMH	70	175
Li-metal-ion	100	200
Compressed H_2		
350 bar	2,000	700
700 bar	1,666	1,165
Liquid H_2	1,885	1,400
Hydrides		
Low temperature	535	2,000
High temperature	1,880	1,600
Activated charcoal	2,000	1,000
Hydrocarbon	11,660	8,750

Table 5.2. *Comparison of energy densities of batteries and hydrogen*