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Investigation on Storage Technologies for Intermittent Renewable Energies: Evaluation and recommended R&D strategy

INVESTIRE-NETWORK

STORAGE TECHNOLOGY REPORT
WPST8-PNEUMATIC STORAGE

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WP ST8-PNEUMATIC STORAGE
(COMPRESSED AIR STORAGE)

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1 Overview of the Storage Technology

1.1 Present technologies

For storage purposes, air must be compressed and expanded with acceptable efficiencies: this imposes good mechanical design and a concept yielding an almost ISOTHERMAL PROCESS; three basic systems are known and should be discussed:

- The liquid piston design (basically the standard free surface accumulator with dissolved gas-in-liquid restitution, Fig. 1), which experiences an almost perfect isothermal behaviour due to the low speed of the compression/expansion process which is distributed over all the storage vessels and hence linked to an enormous heat exchange surface. The power is transmitted to a fast running shaft of a compounded electro-hydraulic motor/generator.
- The air-to-oil interface system, which transforms the air pressure into oil pressure by cyclical expansion or compression phases (0,2 to 1 Hz) and maintains acceptable isothermal conditions thanks to an oil-air heat exchanger integrated in the piston work chambers of the interface; this design uses the oil as heat transfer and power transmission fluid which also links the process to a fast running shaft with flywheel (Fig. 2).
- The direct air-to-shaft link is usually realized as fast running expansion system, either for vehicles based on pistons (Nègre or Miller) or turbines (ABB/Alstom), which have all in common that they cannot be reversed to compress the air again or use fuel for expansion and therefore are not suitable for stand alone systems. In the kW/kWh-range which is the scope of INVESTIRE, direct drive systems have such a low efficiency (< 50%) that they must be considered as mere curiosity.

1.2 History

Energy storage in compressed gas is an old technology for both stationary and mobile equipment; stationary systems were closely linked at least in the early years to hydraulics, the hydro-pneumatic accumulator being mentioned in 1812 by the father of hydraulics (BRAMAH patent # 3611), where the system was to include *"a number of capacious air vessels or loaded pistons…causing a heavy pressure upon the water"*! This principle was used for machine tools like presses and for cranes in the dockyard. Around 1850, air vessels acting on hydraulic fluid were introduced on gunboats for turret controls: this can be considered as the shift to mobile applications.

Vehicles using compressed air storage as driving power appeared first as mining locomotives back in 1860, tramways were used in Paris and Nantes (system MEKARSKY) from 1876 on and in Berne at the end of the 19th century.

Storages on a much bigger scale (580 MWh/290 MW) were realized using dry salt rock caves close to Bremen by BBC in 1978 for air pressures up to 75 bar using ABB/Alstom turbines with added burner re-injection; as these systems run under the abbreviation CAES (Compressed Air Energy Storage) we should stay with the name "pneumatic storage" or Batteries with Oil hydraulics and Pneumatics" (BOP) to avoid confusion.

2 Technical characteristics and applications of the technology

2.1 Components and materials of the technology

A) THE LIQUID PISTON

This arrangement is the direct extension of the hydraulic accumulator principle provided in the simplest version with a high efficiency positive fixed displacement pump/motor 1 controlled by solenoid powered 4-way spool valve 2 which works in a PWM servo-loop with the flywheel 3 designed to maintain a low-rippled speed for the EC motor/generator 4.

The gas volume 6 in the vessels 5 is modulated according to the energy content of the system, pressures varying usually from approx, 100 bar (defined as "empty") to 250 bar (more than 50 % of the vessel filled with liquid 7), which allows to use standard CNG or gas delivery bottles and equipment ranging from valves, pressure switches and other control gear. Of course the oil volume must fit into in the expansion reservoir 8 on the atmospheric side of the system.

This liquid piston gas storage system is certainly the only short-term alternative to lead-acid batteries, as it can be compounded with off-the-shelf elements (except for some control parts and gas-in-liquid compensation); so, prices, performances, weights and volumes can be sorted out quite accurately, but its high storage weight and volume will limit its application field to high power linked to low capacities.

B) THE AIR-TO-OIL INTERFACE

With this solution, the volume of the vessels is only filled with storage air, so the needed cylinder volume will be approx. 10 times smaller than in A) for the same storage capacity. To introduce this improvement, we must add to the already described elements 1 to 5 an interface 9 with a control valve 10 and a heat exchanger 11 which will allow for the isothermal process to take place during compression and expansion, the interface work chamber exchangers being maintained close to the surrounding temperature by the liquid return/suction flow of 1 passing through 11. As here the air is taken from the atmosphere (compression) or exhausted (expansion), a muffler/filter arrangement 12 is needed. Comparing to A) we loose about 5-7 % efficiency, the anti-corrosion effect and the off-the-shelf availability (a new element called Interface must be developed, which will certainly double the price of the hydraulics and converts the development in a long-term matter); on the other hand, we get rid of the oil reservoir and reduce the storage volume and subsequently the asymptotic costs.

Fig. 1: The liquid piston lay-out 2A

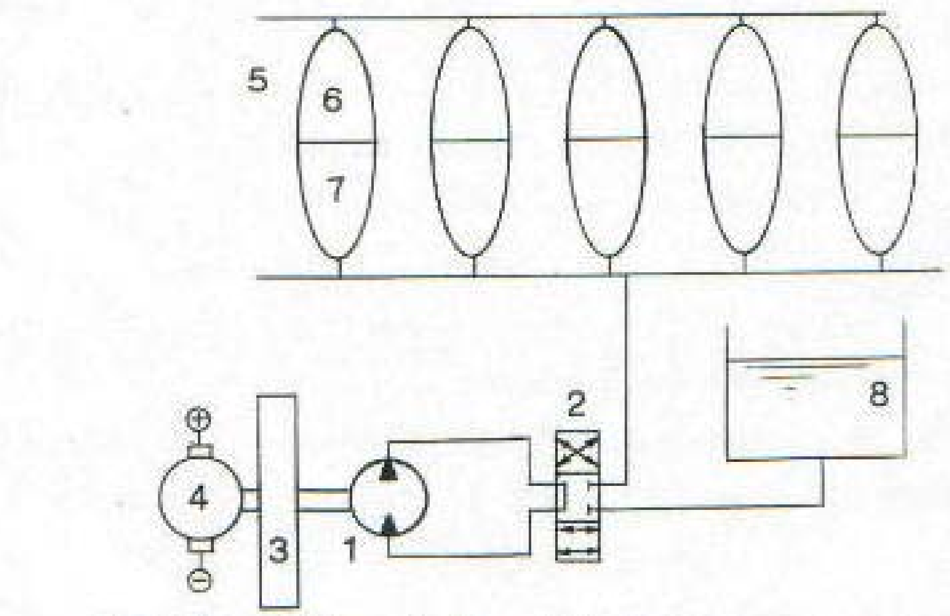
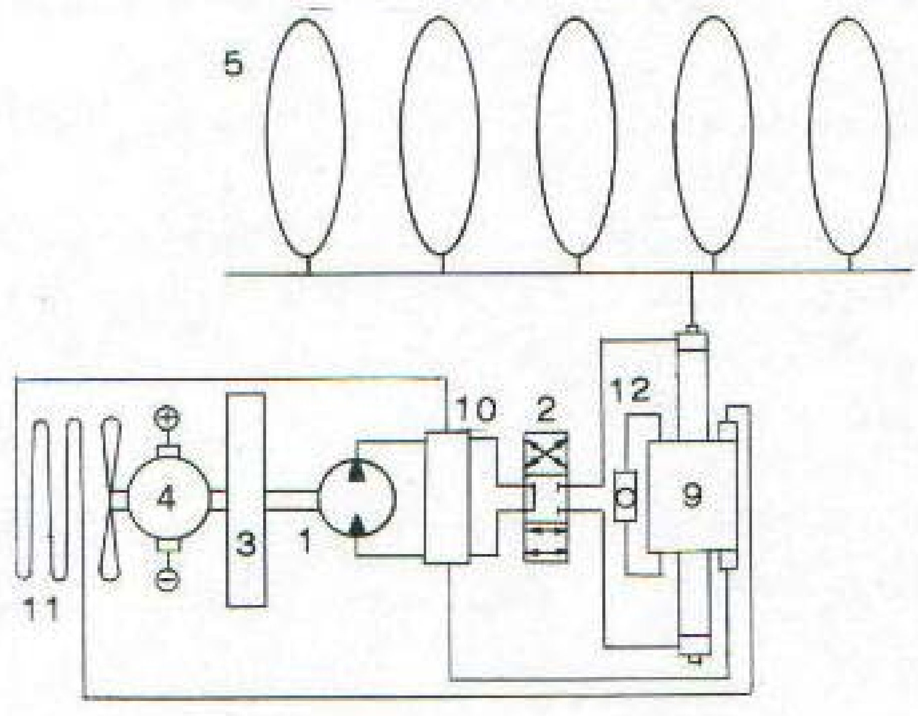


Fig. 2: The air-to-oil interface lay-out



2.2 Data and performance characteristics

2.2.1 System voltage

For both the A) and B) storages, all the voltage values are adaptable design parameters, as they are linked to the motor/generator layout. The fluctuation is bound to the flywheel inertia-to-transmitted power ratio which is controlled by the PWM hydraulic circuit governed by a speed or voltage sensor. Typical design values are ± 5 % with a frequency of 1 to 20 s.

2.2.2 Range of capacities

The charge/discharge rate is not linked to storage capacities, but to the air-to-wire transformer rated power; temperature influences slightly the performances through the viscosity variation of the oil; with special oils, temperatures down to – 40 C can be accepted, standard range would be – 10 up to + 50.

2.2.3 Energy and power density

If the storage capacity is big compared to the charge/discharge power (negligible transformer volume and weight) we get for system A): 2,5 Wh/l and 3,2 Wh/kg for steel CNG 1 cylinders (5,55 Wh/kg for carbon fibre CNG4 cylinders) for a working pressure range up to 250 bar; for system B) we get 25 Wh/l and 20 Wh/kg in steel and 50 Wh/kg in carbon fibre (efficiency not computed).
These figures are of course bound to the maximum acceptable working pressure, doubling this pressure level would yield double Wh/l and increase the Wh/kg by a factor 1,5 approx. (there is no clear technological barrier to higher pressures up to 600 to 700 bar except rising noise abatement problems and availability of long-lived hydraulic elements like pumps/motors; the standard in hydraulics shifted in recent years to 315 bar (4500 psi) so the above figures given for a max pressure of 250 bar underestimate the potentiality of this technology considering the present state-of-the-art.

2.2.4 Cycling service and lifetime

Cycling is not dependent of charge/discharge profiles, as long as the power stays within the transformer design limits; 100 % DOD according to CNG 1 standards must reach 20’000 cycles (1000 cycles per design year; CNG 4 cylinders reach 100’000 cycles!), so a 1 kWh steel storage would yield 20’000 kWh cumulated energy.

2.2.5 Faradic and energy efficiency

Energy efficiency for 1 cycle (charge/discharge) is 73 % for A) at medium power; (predicted 60 % for B); newest developments tend to improve these figures.

2.2.6 Self-discharge.

No self-discharge when the circuit valve is tightly closed (open circuit condition), 40 W for voltage stand-by with a 1,5 kW transformer (development target < 10 W).

2.2.7 Temperature

If no fast temperature change occurs, temperature influence is circumscribed to slight efficiency changes in the hydraulic pump/motor. Standard oil range is - 10 °C up to + 50 °C, with special oil - 40 °C should be possible.

2.2.8 Possible degradations during operation

Overcharge is impossible, as the system is protected by a relief valve in the hydraulic circuit; input power can also be disconnected by a pressure switch; both elements react with great accuracy as pressure reflects the SOC and can be monitored with a simple pressure gauge.

The storage can stay years without charge (empty) suffering no damage, in the nitrogen-filled liquid piston even corrosion is avoided.

2.2.9 Recommended practices

As no acid is involved, installation is a straightforward nuts-and-bolts act (2 pre-assembled pipes interconnect every bottle/cylinder. No short-circuit, hotspot, cell inversion or difference in age have to be considered and the vessels are not fragile transportation goods. Of course no charge regulators or low voltage cut-offs are needed: as the relationship between pressure and SOC are really unambiguous, SOC-related processes can be accurately governed by as many pressure switches as necessary.

2.3 Present situation of the storage technology

2.3.1 Technology developers and manufacturers

The first field of application will be two-cycled (village lighting + food processing at daytime) or three-cycled (milk cooling with hot batches in the morning and afternoon + maintaining cold temperatures at night) systems, with min. 1 kW / 5 kWh capacity.; the product is not yet on the market, but the performances of the A)-version are quite predictable as it consists of a particular arrangement of well-known elements whose lifetime figures can be assessed quite accurately.

2.3.2 Constructional features and manufacturing methods

The main element is the storage vessel which is either a plain steel bottle (CNG 1) or a carbon/glass filament wound cylinder with polyethylene liner (CNG 4). CNG 1 is well suited for A)-type storage (no corrosion as nitrogen is used as storage gas) and CNG 4 is well suited for B)-type storage (the cylinder is resistant to corrosion which would take place because of water condensation in the compressed air). Both vessel types have well-established manufacturing processes, but carbon fibre tanks are approx. five times more expensive (but also three times lighter) than steel vessels (glass fibre lies in-between). Most countries have ailing steel industries which would certainly appreciate the market of the A)-type liquid piston storage.
In the transformer, standard hydraulic elements (broken axis piston pump/motor, solenoid powered 4-way spool valve) do not need special design, as efficiencies and solenoid consumption can be considered good enough for the first series: if in- and output would be shaft-to-shaft, storage cycle efficiency would reach 83 %!
For wire-to-wire applications, the choice of electronically commuted DC motors/generators reaching efficiencies beyond 90 % over a wide range of power is also straightforward, but a special design must be found if voltage standby is to be realized with lowest consumptions and if electronic transformation or buffer batteries are to be avoided.
For the maintenance see “operating characteristics” under # 5.2.

2.3.3 Main conventional applications

The application field of the A)-type storage covers a big choice of stationary equipment where it can compete in price and performance with lead-acid batteries; this is possible for lower capacities combined with great power, especially when other conditions hamper the use of electro-chemical systems (high cycling rate, high or low temperatures, need for accurate energy monitoring, sites of difficult access, explosion-proof installations, need for high

quality AC output etc). The first targeted applications are stand-alone systems with drives mainly for workshops, food processing, milking and UPS installations. The only true operational limit are today the losses at voltage stand-by; the other limitation may be the deliverable power, which is a separate design parameter of the transformer. On the other end of the capacity range, also equipments with long shut-off periods are a good target for pneumatic storages (e.g. seasonal food processing).
Due to its compactness and low weight, the B)-type storage is targeted to cover more demanding systems, with a possible extension into mobile applications like boats, lifts, fork-lift trucks etc, and possibly long-term seasonal storage.

2.3.4 Present R&D actions

2.4 Objectives, targets and deadlines

The type A) storage is in a prototype development stage which should end in the second half of 2003 with some operational wire-to-wire storages for the first stand-alone field experiences (food processing with milking machines in the Alps and millet milling in northern Senegal, telecom antennas in Germany) in 2004. An important effort will be to qualify the hydraulic circuit with environment-friendly glycol-based fluids or locally available oils (e.g. peanut oil).
Type B) needs a type A) transformer with an interface system added; the first interface works already as functional module in the compressor mode and substantial efforts will be needed to reach maturity as lifetime issues must be considered; efforts are also made to develop a B)-type without seals using also some kind of liquid piston.

3 Economical issues

3.1 Cost of the storage technology

As capacities and rated power are not linked, the storage price must be computed adding the asymptotic storage price (where the transformer price is neglected) to the transformer price: here the details of typical OEM cost:

A. The liquid piston

Hydraulics 700 €, EC motor/generator 200 €, both for 1500 W; vessels are at 1,5 € / lit (CNG 1 according to ISO 11439, where 1 lit stands for 2,5 Wh with a pressure range up to 250 bar (standard CNG values). So, a 10 kWh-storage with 1500 W in/output will cost 7900 € or **0,79 € / Wh,** the asymptotic cost drops to **0,7 € / Wh.** If water-glycol fluid is used, asymptotic price would be **0,65 € / Wh** (when transformer price is negligible compared to storage).
NOTE: if the cylinders are manufactured locally, price may drop down to 0,8 € / lit: a 10 kWh/1,5 kW storage would then cost 5100 € or **0,51 € / Wh**, the asymptotic price being here **0,42 € / Wh**.

B. The Interface system

Here we get of course premium figures for the asymptotic costs based on 25 Wh/lit with negligible oil volume. Admitting that the interface triples the hydraulics costs (2100 € instead of 700 €) a 1,5 kW / 10 kWh would reach 2900 € with steel vessels, or **0,29 € / Wh,** leaving the asymptotic figure at **0,06 € / Wh: a true candidate for the book of records!**

These figures must be considered as rough estimates, as a lot of ancillaries cannot be integrated in the evaluation at this stage (collapsible tank and piping for A, possibly air dryers for B if CNG 1 vessels are to be used, all these concepts and many others being dependent also from legal standard application rules which do not exist for this kind of technology), but we hope to stay within 20 % of high volume OEM pricing once a substantial market can be established.

Power electronics is needed in both concepts only for the motor/generator which transforms the shaft-to-shaft storage into a wire-to-wire storage; these power elements are integrated directly in the machine and various choices are possible between different off-the-shelf solutions, the criteria being efficiency in a broad power range and lowest idling losses.

Internal control electronics is needed for the A type storage for the timing of the hydraulic PWM power adapter (solenoid control to maintain in/output voltage within a pre-determined range), whereas the B type uses a more intricate control gear to be added to the A-electronics, as stroke control and process governed expansion timing must be integrated.

3.2 Installation, operating and maintenance cost

Taking the 10 kWh-storage and choosing the conservative figure of 20’000 cycles fixed in the standard, we get a global delivery through the storage lifetime of 200’000 kWh, which yields 0,035 €/kWh with the asymptotic upper pricing (1,5 € / lit) for the A type and 0,0032 € / kWh for the B type; with a 3-cycle/day operation we would get almost 18 years of operation or 80’000 running hours at 12 h/day: as MTBF of the transformer hydraulics is targeted at 30’000 to 40’000 hours, we should add one full change of the hydraulic motor once in the lifetime of the bottles (700-1000 €), which will increase the 10 kWh-figures by less than 10 %.

For the A-type, oil changes are not necessary with most transmission fluids as they are not exposed to oxidation (total confinement with nitrogen) and temperature stays close to ambient conditions.. An oil change with vegetable oil is not expensive and similar experiences show that a change after 10 years is quite adequate even in hot countries, moreover the old oil can be used for livestock food (note that in this type A)-storage the oil does not age through shear stress, as average displacement per kWh is only 150 lit so that the full oil content experiences shear through the motor/pump every 10 kWh or 20’000 times in the above mentioned lifetime: more than 5 times less than for a car engine in 1000 hours where the thermal stress must be added).
The B type oil volume (some 40 lit for a 1,5 kW unit) has no major financial effect even if a change should be needed every two years; these details cannot be determined at the present stage.
The installation costs amount to 5-13 % of the storage OEM value as local labour costs have a major influence (the vessels are delivered with a nitrogen filling to the mounting place where a concrete sump bigger than the oil volume must be prepared and topped by skids to support the vertically stacked bottles); freight expenses should be similar to a tubular battery stack designed to yield 3000 cycles with the same capacity, but without the forwarding problem of acid and fragile material; moreover, the bottles can be generally bought in the targeted area or country as there is almost no spot on this earth where these bottles are not available or even produced locally, this implies the advantage to have a perfect accordance with the customer’s standards (what finally must be shipped is basically a 1,5 kW transformer which does not exceed 19 % of the weight of a 10 kWh storage).

4 Environmental Issues

4.1 Current knowledge on environmental issues of the storage technology

For a 10 kWh/1 kW type A)-storage (3940 kg) we need 3910 kg of steel, 1 kg of hardened steel, 2,5 kg of copper strips for the motor/generator, 0,5 kg of magnetic material (not recyclable but reusable, and 30 kg of rubber canvas for a collapsible reservoir. As hydraulic fluid we use either glycol based or vegetable oil which have almost no recycling problems (see 3.2).
The B)-storage has a much better environmental record, as the steel volume is much smaller (8 to 10 times when compared to the A)-type), no collapsible tank is needed and the oil volume is almost negligible.
The pressure vessels have a good safety record as gas delivery bottles (3 heavy accidents in Germany in 100 years) as they are over-designed in terms of resistance because no safety valve can limit the pressure even when significant pressure increase occurs due to climatic or accidental heat-up. In both BOP storage types an accurate safety relief valve limits the pressure in the hydraulic circuit and the bottles are not moved under pressure as for gas deliveries: the operating condition are incomparably more favourable in this stationary storage lay-out. Old bottles have a good scrap value as they can go to the foundry with no dismantling work, but they are also welcome as building material for pillars or other welded structures.
The energy input requirement for manufacturing (“grey energy”) has been quite accurately calculated by an independent cylinder company for both filament wound CNG 4 vessels: we get for a 100 lit cylinder with glass fibre wrapping **1051 kWh** and **1503 kWh** with carbon fibre using the same polyethylene roto-moulded liners. With a B-type storage we need **0,37 kWh / Wh** (glass fibre) which yields an energy payback at 370 cycles (555 cycles for carbon CNG 4): this is just 2,7 % of the minimal design life of 20’000 cycles!
Both hydraulic and pneumatic piping are of smallest possible diameter to avoid strong jet effects if torn away and no cell polarity inversion and hot spots can occur like in lead-acid

battery stacks. Even if the storage has to work with high voltages on the wire side, no danger will emanate from the stack.
Noise does not exceed 85 dB(A) when not protected, but small noise abatement structures limit these emissions quite easily as the source is limited to the rotating electro-hydraulic compound.

4.2 Improvement options

*E*xcept for the fluid compatibility and the noise abatement there is no big technical improvement potential; both nuisances are linked to improvements in the hydroelectric compound (hydraulic and electric motor/generator part of the transformer), with special mention of the flywheel optimisation. Efficiency is also linked to this transformer, so most efforts have to be invested here, also to reduce voltage stand-by losses; a big step in the improvement of the environmental profile of the technology would be to use lighter steel bottles as the requirements are less stringent for the BOP storage application than for the special gas delivery business, but such a step would be very expensive and should be considered only after some years of successful market introduction; the vessels for the B-type must cope with condensing water introduced by the compressed air: here different solutions must be analysed, together with the correct fluid choice.

5 Application of the storage technology for RES

5.1 Existing applications

The type A) storage which is now at prototype stage is tailored to fit various types of stand-alone systems which are already working with lead-acid tubular batteries (see 2.3.3 for conventional applications), where generally several cycles per day are expected (milk cooling, villages with workshops and/or food processing).

5.2 Operating characteristics

The type A)-storage is close to an install-and-forget system as no chemical process is involved and little periodic maintenance is needed; with the legal pressure vessel check every 5 years an overhaul of the transformer can be scheduled based on plug-in exchange (13 % of the price 1,5 % of the weight for 10 kWh/1,5 kW). No corrosion is to be expected, as nitrogen is the working gas: the only mishap could be a leakage which can be easily monitored by a level switch in the sump basement.
90 % of the used elements are standard off-the-shelf products from the hydraulic, gas or CNG industry with known reliability records and routine practices with worldwide acceptance.
Untight mounting of the piping may impose nitrogen backup injections but leaks can easily be identified by bubble foam or soap water, in any case assembled piping will be delivered for ease and correctness of mounting.

5.3 Assessment of the storage technology in these applications

The BOP storages cover similar application to lead-acid batteries with advantages and shortcomings:

<u>The advantages:</u>

- enormous cycling capacity with almost no ageing
- possibility of breakdown limited to the transformer unit (small cost, negligible weight, plug-in exchange).

- Accurate monitoring of stored energy by simple pressure gauge
- Fast refilling by plug-in docking of emergency hydraulic unit for A or by fast scavenging for B (in case of array breakdown or bad meteorology)
- No charge regulator or low-voltage cut-off control needed (relief valve or pressure switch define upper charge limit, 100 % DOD maintained for long periods does not damage the storage), no complex battery management algorithm and floating period are needed.
- No acid is involved, thus limiting transportation problems.
- No dangerous gases emitted in operation, no floating period needed for full load.
- Over sizing is allowed as no stratification occurs: bigger storage capacities are more economic due to lower price effect of the transformer.
- High power storage can be designed with small capacities (power-to-capacity ratio is a design parameter), a small unit can be replaced by a stronger BOP transformer at any moment.
- Direct hydraulic drive or AC output can be hooked on the hydraulic circuit.
- Extended temperature range at the cold and hot end of the scale (-40 C to + 50 C).
- Uses well established technologies with little technological and reliability risk

Where the systems are more or less equivalent:

- The A- type is slightly more expensive than lead-acid if no other operational characteristics can be weighted financially; price break-even between 5 kWh and 10 kWh when compared to lead-acid (300 0 cycles) for B).
- Fluid quantities involved: lead-acid is 25 % of A), but fluid is more dangerous (acid); for B), the fluid is 10 times smaller than for lead-acid (40 lit of oil).
- Efficiencies (the full cycle charge/discharge efficiency of 73 % for A)-type is higher than for old batteries, especially if gassing is accounted for). This figure is not submitted to ageing.
-

Weaknesses:

- Heavier and bulkier than lead-acid in the case of A), but shipping costs may be much lower (local supply)
- Not negligible voltage standby losses (idling) which correspond to 3,4 % of the rated power of the transformer, which is equivalent to a self-discharge rate of 12 % per 24 h with a 10 kWh storage (will be similar to idling inverter losses).
- Generates periodic audible noise as the transformer mobile elements run at 3000 4'500 rpm.
- Possible leakage in the pneumatic and hydraulic piping (straightforward nuts-and-bolts problem which can be fixed on-the-spot).

5.4 Potential future applications

The BOP storages can be tailored to fit a majority of lead-acid stand-alone applications, some features open new fields to storage design, as wire-to-shaft, shaft-to-wire and wire-to rod (linear movement) combinations are feasible under arctic and hot countries conditions. To explore all the implications of these new possibilities will be the first task once the standard system will be marketable; due to its volume and weight, type A systems will certainly fit small capacities with high power like UPS or mini-grids with a supply-cycle of 24 h (solar input), type B may be eligible for greatest storages up to seasonal systems.

COMPARISON OF STORAGES (MAX. WORKING PRESSURE 250 BAR FOR BOP)

Characteristic	Fluid piston (A)	Interface (B)	Tubular lead-acid
Volume for a 10 kWh storage	5000 L (vessels 4000 L)	450 L (vessels 400 L)	735 L*
Weight for a 10 kWh storage	5760 kg - 2960 kg**	500 kg - 170 kg**	1530 kg*
Fluid	2208 L (Oil, Glycol or Water)	40 L (Oil)	402 L* (Acid)
Volumetric energy density (inclu-ding ancillaries)	1,6 Wh / L	24 Wh / L	13,6 Wh / L*
Grav.. energy density (including ancillaries)	1,75 Wh / kg - 3,3 Wh / kg**	23,2 Wh / kg - 50 Wh / kg**	6,5 Wh / kg*
Self-discharge with voltage stand-by, 40 °C, 10 kWh, 1 kW.	14 days	10 days	approx. 180 days
Self-discharge, no output (tight vessels)	Years	Years	approx. 180 days
Damage in case of full discharge	none, but gas in motor (noise)	none	important-terminal
OEM costs‘‘‘	0,92 € / Wh	0,1 € / Wh - 0,4 € / Wh**	0.49 € / Wh *
SOC monitoring	Pressure gauge 1%	Pressure gauge 1%	by voltage check (not accurate, varies with age)
Danger	Leakage (oil or gas jet) basically explosion-proof	Leakage (oil or gas jet) basically explosion-proof	Recombinant H/O near sparks
Fast charge	less than 1 h with hydropump auxiliary vessel	less than 1 min from **needs a long added period**	several hours, final floating
Cycling	basically unlimited	basically unlimited	depends from DOD
Storage capacity	does not change	does not change	declines with age and speed of charge
Temperature range	-20 to 45 °C (limitation is collapsible tank and fluid)	-40 to 55 °C with two oil ranges **can be adapted to arctic cond.**	limited range by electrode Corrosion & freezing
Max. power delivery	any, sizing of transformer **Not linked to capacity**	any, sizing of transformer **Not linked to capacity**	in A: 10% of Ah capacity
Interchangeability	all ages with same height	all kind of models and ages	same model and age only
Stratification	none, over sizing possible	none, over sizing possible	very strong if oversized
Energetic efficiency, full cycle			
Wire-to-Wire	0.68	0.6	80 % (new) / 60% (old)
Shaft-to-Shaft	0.84	0.68	65% (new) / 50% (old)
Voltage fluctuations	5%, related / Flywheel cont.	5%, related / Flywheel cont.	-11,5% / + 20%
Suitability for mobile applications	no	yes	no
Recyclability	medium, PVC collapsible tank, and a lot of steel	very good, no plastics and **little steel**	bad, plastics and heavy metals in lead

*) with rated life of 3000 cycles (DOD 28%, 40 °C, I5) **) carbon filament wound CNG 4 ISO 11439
***) steel vessel cost 1,6 € / liter

6 Needs for R&D for an extended use in RES

Extended use of renewable energy needs extended storage capacities which go far beyond the possibilities and the operational limitations of lead-acid storage and there is no other solution at sight. Type A) fluid piston seems to be potentially able to cover a part of this field on a mid-term scale (5 years) as soon as the present development stage ends (2003/2004) successfully, whereas a sustained development effort in the interface system (type B)-storage) will open a long-term perspective as it would divide storage volume and weight by almost a factor 10 and using CNG 4 would open the door to some mobile applications; hereby a transmission fluid with lowest possible air solubility must be defined.

7 Conclusion and Recommendations

Squeezed between excessive cycling if batteries are undersized and incomplete charging if oversized, lead-acid batteries are surrounded by a lot of life-reducing factors and the only escape lane seems to be more and more sophistication in the electronic management which very often looks like a plaster: there is not enough flexibility to respond to seasonal or assignment changes.

The BOP storages claim to have not so strong shortcomings, which would open the way to simplified planning, high reliability and environmental safety. So, the recommendation should be to thoroughly analyse the potential of this technology to sort out the pending questions.

8 Glossary and Abbreviations

The BOP technology is a compound of Compressed Natural Gas elements with oil hydraulic concepts, so the detailed terminology can be completed by specific literature in theses areas.

CNG	Compressed Natural Gas (followed by 1…4 according to ISO 11439)
Isothermal process	in gas thermodynamics, when changes occur without temperature variation
CAES	Compressed Air Energy Storage (generally turbine systems with fuel burner)
BOP	Acronym for Batteries w. Oil hydraulics & Pneumatics, where oil links air/gas to hydraulic motors/pumps with fast running shafts.
BOP transformer	hydraulic gear between gas and shaft (or wire), with PWM 4-way valve control
Vessel, bottle, cylinder	different names for high pressure gas tanks in different business areas.
Carbon filament	fibre for cylinder winding with high tensile strength and no cyclical fatigue
Working pressure	standard working pressure for vessels at 15 °C with temperature limit 65 °C.
Solenoid	electromagnetic control for 4-way spool valve

9 Bibliography

[1 Schneider, Urs: Pneumatics and energy storage (Forschungsbericht Bundesamt für Energie 1999)

[2 van Haaften et Al.: future vehicle drives, comparing compressed air to fuel cells (Institut der Umweltwissenschaften der Universität Zürich, 2000).

[3 Menhardt, Walter: Compressed Air as Driving Power versus new and old fuels (Forschungsbericht Bundesamt für Energie 2001)

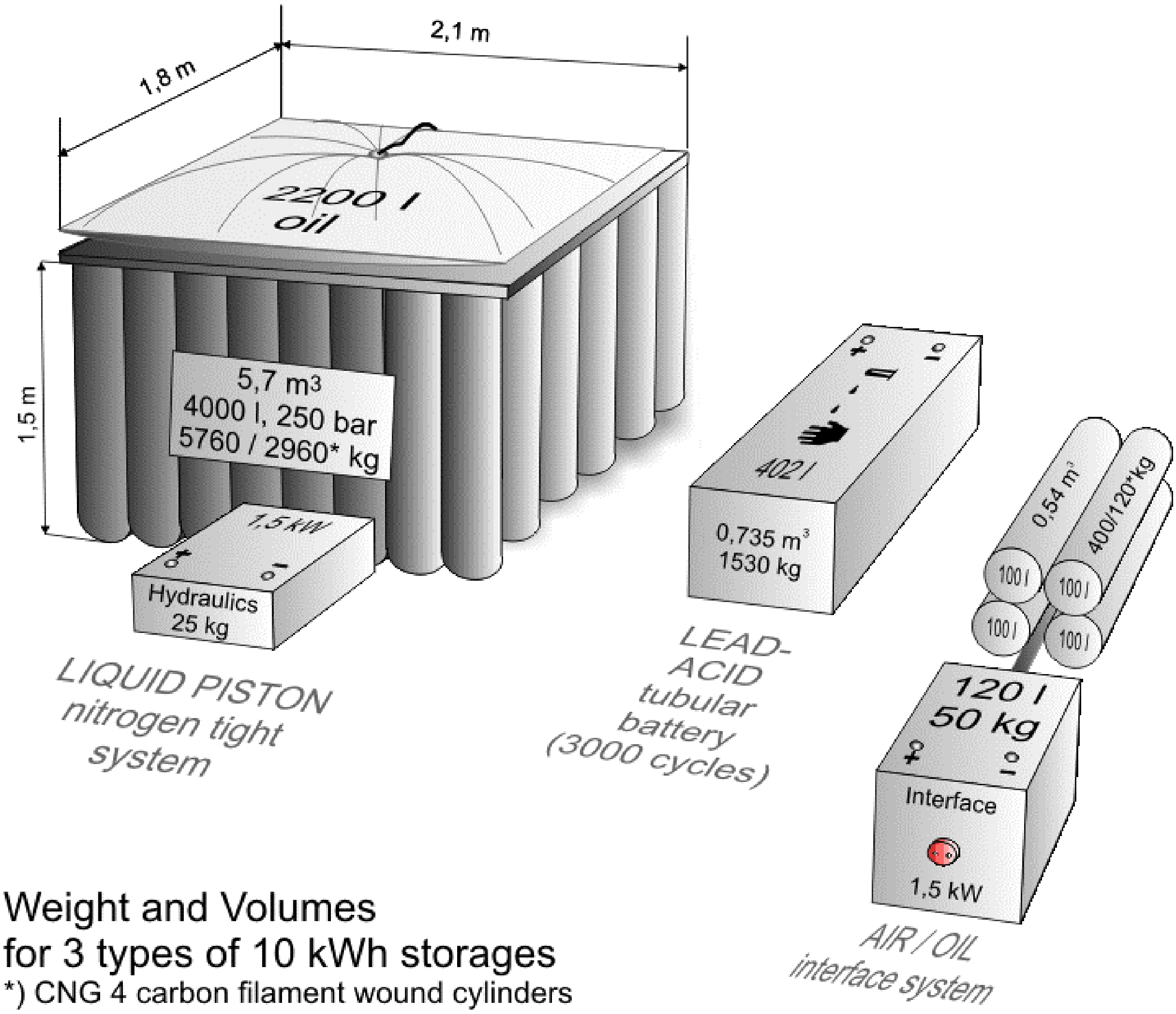
[4 Guillon, Marcel: Commande et asservissement electrohydraulique, (Lavoisier Tec&Doc 1992) high-tech oilhydraulics with exhaustive calculus of pneumatic storages and losses in fast running hydraulic clearances aiming at efficiency improvements in oilhydraulic machines.

[5 Cyphelly Ivan: Fast Filling of Air and CNG high pressure Cylinders by Scavenging (Forschungsbericht Bundesamt für Energie, 1998).

[6 Tuschy et Al.: CAES with High Efficiency and Power Output (VDI-Bericht 1734 “Energiespeicher”, 2002)

For rural decentralized electrification: www.alternativascmr.com
For the MEKARSKY air tram story www.filotram.com

For more detailed knowledge: the Patents of Terry Miller, Guy Nègre and Ivan Cyphelly



Weight and Volumes
for 3 types of 10 kWh storages
*) CNG 4 carbon filament wound cylinders