Offshore energy storage in deep waters for floating wind mills

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Introduction : a comparison of energy storage techniques

Renewable energy resources like wind and sun, but also tidal systems or wave energy, cannot produce the same level of energy 24 hours a day or 7 days a week. In order to have access to renewable energy supply on a more permanent basis, large scale grid connectivity could be part of the solution. This implies long distance energy transportation. An additional solution is to find ways to store energy temporarily. When the energy production level is higher than the demand, energy can be stored. It can be recovered and consumed in times of high demand and too low production.

Energy can be stored in different ways. Electrical batteries typically transform the electrical energy in an electrochemical way. Other systems store heat in isolated materials (e.g. photo thermal panels with a water reservoir), or with phase change materials. Some countries are fit to hold water in a lake at higher altitude or behind an artificial barrage. Producing hydrogen gas (H_2) and storing it in appropriate tanks for later consumption is another option : it can be burnt or used in fuel cells. Other scientists or searching for ways to convert CO_2 back to carbon chains, using renewable energy. The carbon chains can be stored as gas or oil are stored. They can be burnt again to produce heat and generate mechanical and electrical power the same way as it has been done this for more than a century now.

It is interesting to compare these storage methods. The criteria to choose one type or another, depend on the local environment, and of course the application. For instance: for cars and bicycles the stored energy should be transportable, and have a low weight and small volume per kWh. Some of the storage systems are only interesting for short term energy storage, like the kinetic energy stored in a flywheel. But for some applications that is perfectly alright.

Here is a comparison of different energy carriers, based on their energy density: figure 1 shows the amount of MegaJoules contained in one cubic meter of the material in question.

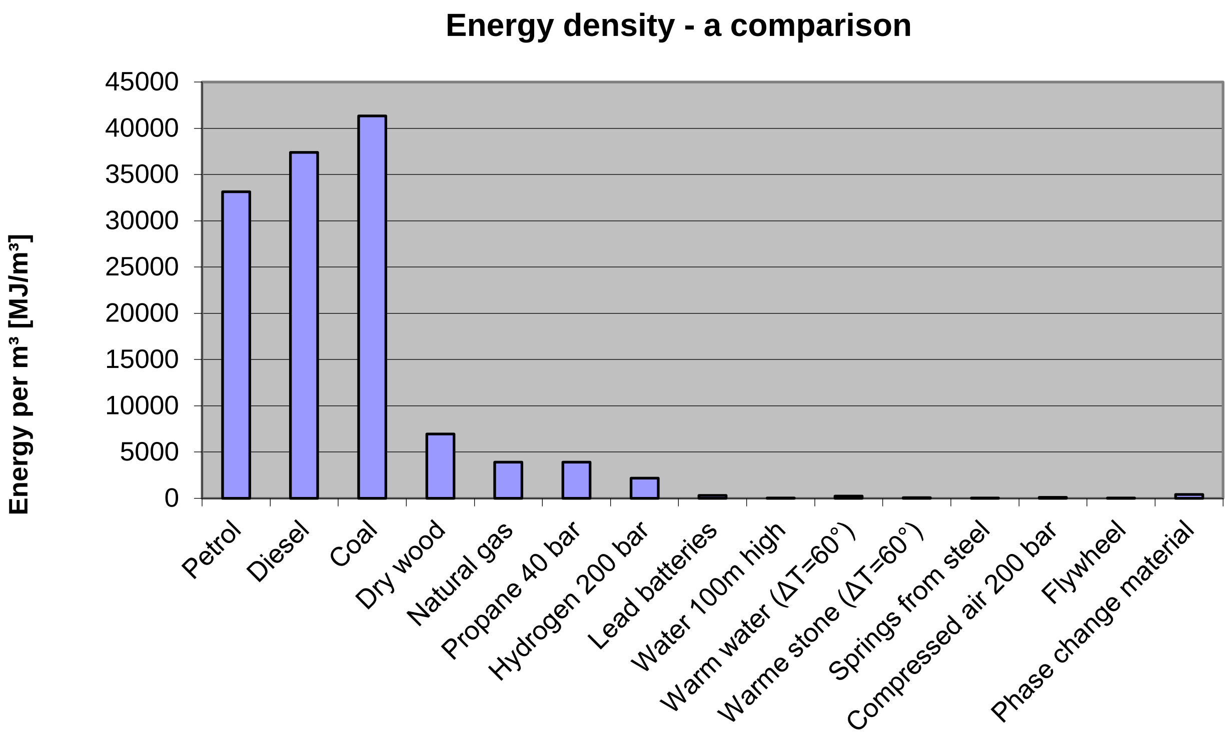

Figure 1 – Comparison of energy per m³ for different resources

From this graph it is obvious that the renewables are far behind on today's carbon based fuels. If these non-renewables are left out of the graph the picture looks like figure 2.

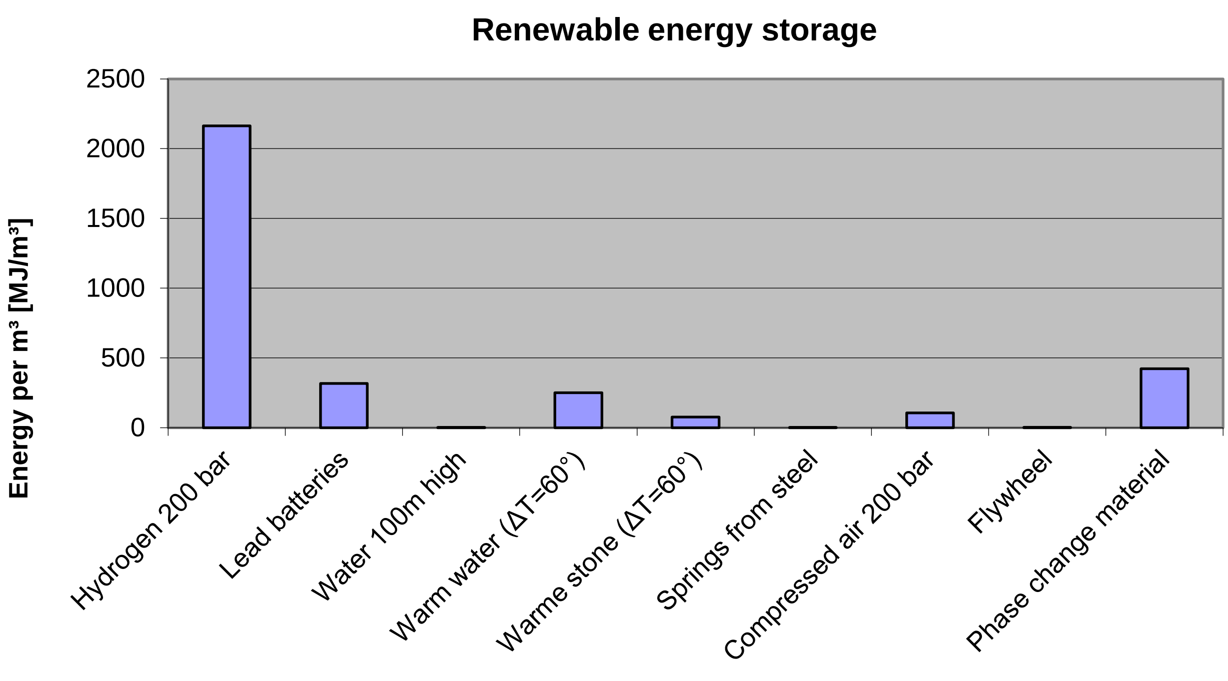

Figure 2 – Comparison of energy per m³ for reversible ways of storage

The following conclusions can be drawn.

- Hydrogen is a very dense energy carrier.
- Secondly, the phase change materials have a good potential, but it is not so evident to convert phase change heat to electrical energy, as the associated temperature change typically is very low.
- Recovering heat from hot water (heat storage) is not a problem. But with for instance 60° of the temperature change applied to a Rankine cycle or a Stirling motor to transform the heat back to electricity, the efficiency is rather poor. Moreover, what system should be thought of if one wants to scale this type of storage ? How to build and isolate huge tanks of hot water ?
- Of course lead batteries are known for decades, and they perform not bad. But is this a technology that can be scaled another order of magnitude knowing today's drawbacks ? Other types of batteries perform even much better, like lithium-ion batteries. But do we have enough of these materials to scale them ?
- Potential energy from springs, or kinetic energy from flywheels show rather poor density. That is also the case for the potential energy of water at an altitude of 100m high. Still this technique is well spread because of scalability : some environments are very well fit for large scale water reservoirs.
- Compressed air storage appears neither super nor bad. But as it will be shown next, a deep water environment offers specific opportunities to scale pressure vessels, opportunities that are infeasible onshore.
- It is interesting to compare compressed air and water storage more in detail. For 100m high water storage, a 200 bar compressed air solution is 108 more dense. But for applications at sea water storage 100m high is hard to realize. What has been considered at shallow seas is an artificial lake e.g. 10m high, as an order of magnitude. If that is compared with compressed air storage at 10 baro then the last one is a factor 27 times more dense.

So compressed air may not be a super dense way of storing energy, but it is at least several times more interesting than potential energy of water. This technique is widely spread in mountain environments, and now also considered for artificial lakes at sea, where for example 10m or 30m difference of water level is put forward. So in case of a deep sea environment why not study compressed air ?

Deep water storage of compressed air

The fact that wind turbines are now also installed floating at the water surface, anchored to the bottom of the sea, triggers the study of energy storage that fits in this environment. This text is a closer look to under water compressed air storage in flexible tanks, for instance textile bags.

First of all, the pressure rises with the depth under water.

$$p = \rho_w . g . h \tag{1}$$

At a depth of 10m there is a pressure of almost 1 baro (relative to the atmospheric pressure) so 2bara. At 100m this is about 10 baro, and at 1000m about 100 baro. This means that if an airbag at that depth is inflated with air using a pipe from the water surface to the airbag, an air pressure of almost the same magnitude as the hydrostatic water pressure at that depth has to be applied. What are the advantages related to this system sketched in figure 3 ?

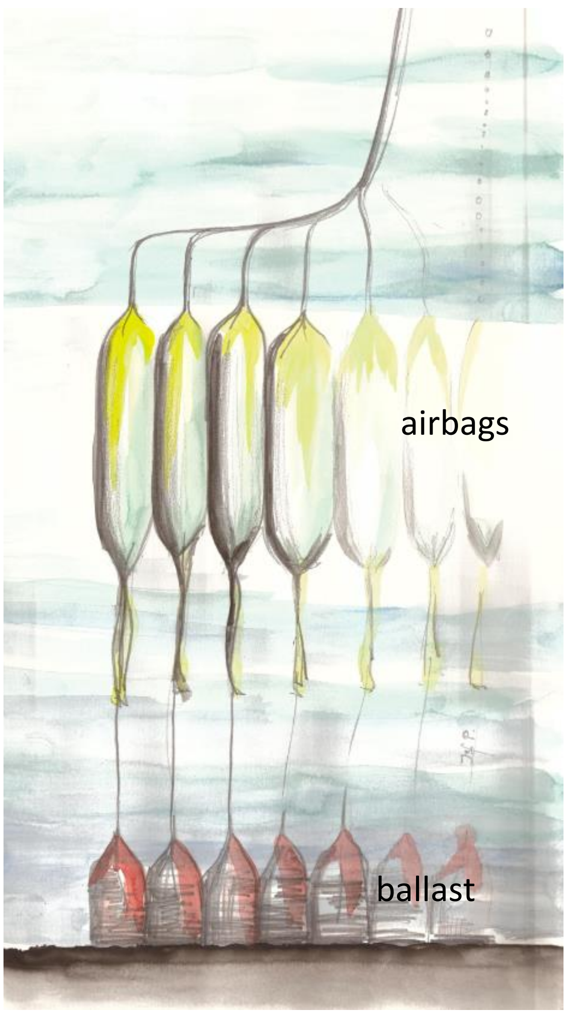

Figure 3 – concept : compressed air stored in airbags deep below the water surface

1) First of all the airbags are in isostatic balance with the surrounding water. So the walls of these pressurized air reservoirs don't need to be super strong, as would be the case with onshore pressure reservoirs. They could be made of impregnated textile, like a rubber boat. Today's technical textiles can be produced on large scale and with specific technical properties for this purpose.
2) That makes these reservoirs easily scalable to large volumes.
3) Another advantage : during inflation with air or during air consumption the air pressure stays almost constant. Whereas a water barrage system changes pressure as the lake behind the barrage is pumped up or turbined down. That is comfortable from a design point of view for the compressor or the expander. It also allows to operate the system at the maximum design power at any time.
4) At sea there is plenty of space to install large volume reservoirs, without disturbing too much the environment. From a safety point of view storing air offshore is somewhat less critical than onshore.
5) If the airbag system is designed properly, it can be pulled up at the end of their life cycle without too much effort or environmental impact. During the life cycle it could even be displaced if that is necessary someday.
6) Several measurement techniques are available to monitor the filling degree of the reservoir. The sensors do not necessarily have to be installed underwater, which is advantageous from a maintenance point of view.

The only trouble is to keep the airbags down.

How much ballast is required to keep the airbags down ?

Due to buoyancy forces, the airbags want to come up to the surface like a balloon. In order to keep them down a ballast is required. This can be sand or another aggregate contained in a textile bag : think of the "big bags" that are used in building construction. Sand, gravel or other heavy bulk materials are available at large scale. But whatever the ballast material is, it has to be clear that relatively big volumes are required. Expressed in formulas :

The forces acting on the airbag :

- Down : the weight of the air = $\rho_{air}.V_{air}.g$
- Down : the weight of the airbag = $m_{airbag}.g$
- Up : the weight of the displaced water (Archimedes law) = $\rho_{water}.V_{air}.g$

The forces on the ballast :

- Down : the weight of the bulk ballast = $\rho_{bulk}.V_{bulk}.g$

- Down : the weight of the ballast bag = $m_{ballastbag}.g$
- Up : the weight of the displaced water by the ballast = $\rho_{water}.V_{bulk}.g$

Putting all these forces together the requirement for the ballast becomes :

$$\rho_{air}.V_{air}.g + m_{airbag}.g + \rho_{bulk}.V_{bulk}.g + m_{ballastbag}.g > \rho_{water}.V_{air}.g + \rho_{water}.V_{bulk}.g \qquad (2)$$

When dropping g in this formula, and neglecting the weight of both bags one gets :

$$(\rho_{bulk} - \rho_{water}).V_{bulk} > (\rho_{water} - \rho_{air}).V_{air} \qquad (3)$$

At 10 baro the density of air is about 13 kg/m³, which is negligible compared to the to the density of water. An error of only about 1,3% is made by dropping it from the formula. At an air pressure of 100 baro, the error of dropping that term is about 13%, so then it could be taken into account. But roughly speaking, one can say that

$$V_{bulk} > \frac{1}{\frac{\rho_{bulk}}{\rho_{water}} - 1}.V_{air} \qquad (4)$$

So if the bulk material is only twice as heavy as the water (about 2000 kg/m³) which is the order of magnitude for sand or gravel, then the volume of bulk material for the ballast has to be as large as the volume of air stored. For safety even a bit more.

From this short analysis it is clear that the design of both types of bags has to hold the forces in between them. And for large systems, they will be quite big. To interconnect the textile bags, it could be interesting to use many lines, as is known from air balloons or parachutes, rather than just a few lines. The bags could also be made large by making many compartments instead of one large bag. In textile weaving it is possible to produce so called “curtain airbags” in one process, so without confection afterwards. They consist of many compartments next to each other in one large piece of fabric.

Thermodynamics of air compression and expansion for energy storage in deep waters

Compressed air has a bad reputation as it comes to energy efficiency. Is that well-grounded or is it just an idea ?

Every technician knows that a compressor, even if it’s a small one, needs cooling. The heat that is produced is certainly a loss in the production of compressed air. But very few people are aware of the fact that almost a 100% of the mechanical shaft energy is turned into heat. Manufacturers of large compressors are well aware, because some of them offer the possibility to heat the buildings or a production plant with this waste heat. The cooler that is accompanying the compressor is then coupled with the central heating of the building.

But if almost all the mechanical energy is lost into heat, then how about the potential energy stored in de compressed air ? And if there is any internal energy left in the air, what exactly happens during air expansion ?

Thermodynamics gives an answer to these questions.

The internal energy U of a certain volume of air changes if an amount of heat δQ is added or if an amount of work δW is applied to that gas:

$$dU = \delta Q + \delta W \tag{5}$$

In thermodynamics this expression can also be written per kilogram of air. Then small letters are used :

$$du = dq + dw_c \tag{6}$$

dw_c is the amount of compression work that is added to the air per kilogram of it. Now, air behaves more or less like an ideal gas in a wide range. And in thermodynamics it is explained that de internal energy of an ideal gas is only function of its temperature T. To be more specific:

$$du = c_v.dT \tag{7}$$

with c_v the specific heat at constant volume. This expression says that for an isothermal state of change ($dT = 0$) the internal energy doesn't change, and hence

$$0 = dq + dw_c \qquad \text{or} \qquad dw_c = -dq \tag{8}$$

So in order to have an isothermal compression one needs to take away as much heat from the air, as compression work is given to the air. And during an isothermal expansion, the same amount of heat has to be absorbed by the air, as the amount of mechanical work that is delivered by the air.

In other words, an isothermal compressor or expander has to be as much a heat exchanger as a mechanical work exchanger.

Modern compressors do not correspond to this definition. Whether it is a piston compressor, a scroll or tooth compressor, a screw compressor or a turbo-compressor, all of them turn at high shaft speed, leaving no time at all for the air to exchange heat with the walls of the compressor. So they have a compression without heat exchange, a so called adiabatic state of change. The air heats significantly as is shown in the p-V-diagram in figure 4. To be clear, the compressor walls will indeed get hot. So there is heat transfer to the walls. But this amount of heat is negligible compared to the heat that should be exchanged to speak about isothermal compression.

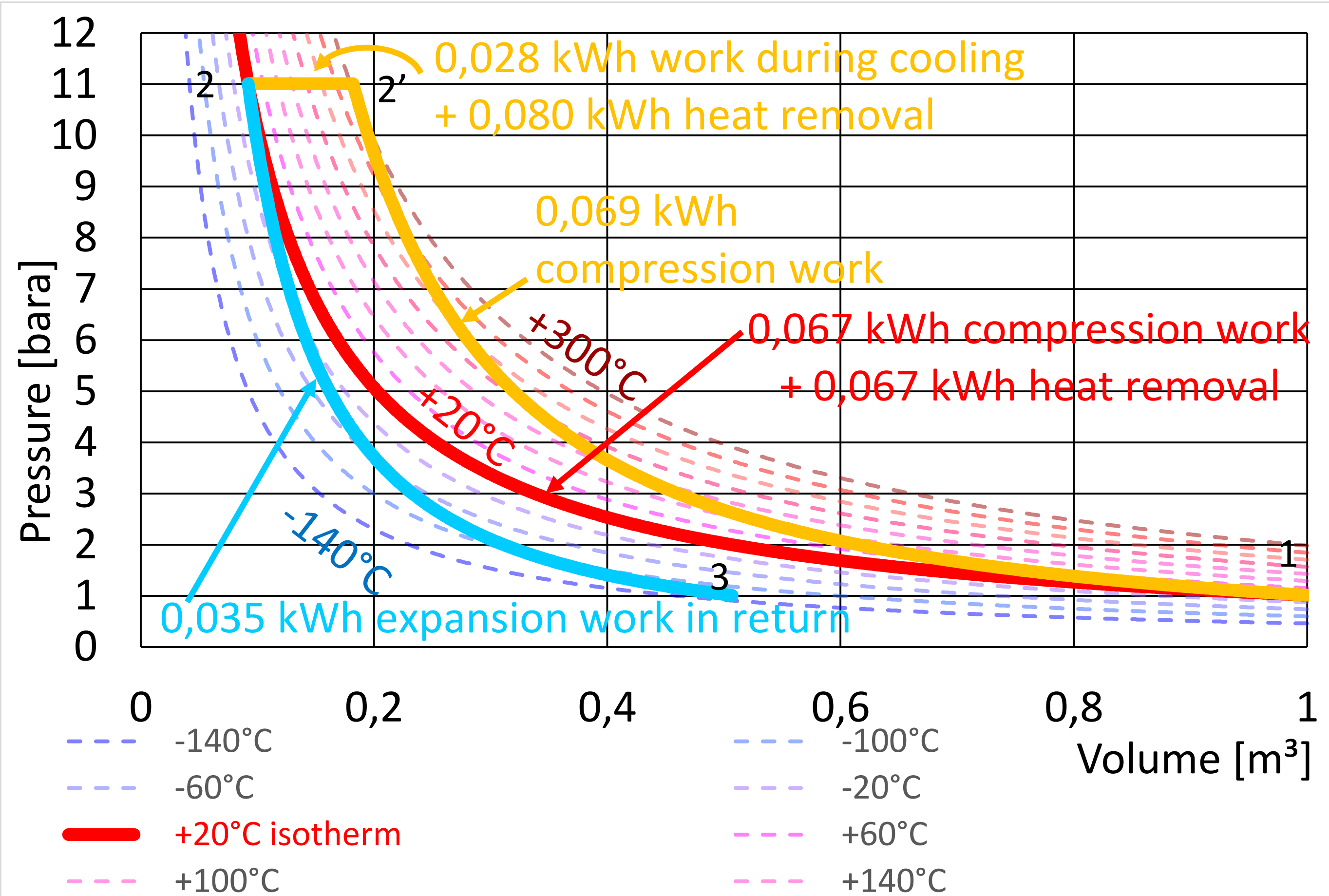

Figure 4 - p-V diagram for the compression and expansion of 1 m³ of air

The red line (1-2) shows the isothermal state of change. As the temperature is constant, it can be learned from the ideal gas law that pressure p and volume V behave inversely.

$$p.V = m.R.T = \text{constant} \tag{9}$$

with m the mass of air, and R the gas constant for air.

The compression work W_c that has to be delivered is given by the surface below the curve :

$$W_c = -\int_1^2 p.dV = p_1.V_1.ln\frac{p_2}{p_1} \tag{10}$$

For a compression from atmosphere to 10 baro, that is 0,067 kWh/m³ (242 kJ/m³). After compression some more work (displacement work) has to be delivered to push the air out of the compression chamber into the reservoir. That would highlight the difference between “compression work” ($dW_c = -p.dV$) and “technical work” ($dW_t = V.dp$), a discussion that leads too far here. What is important here is that, although this amount of work also has to be delivered, it will still be recovered when filling an expander with the right amount of air for an expansion to atmospheric pressure.

The orange line (1-2’) on the other hand shows an adiabatic compression, so without heat exchange, which is more or less what happens in a real compressor. Now the state of change can be described by the formula

$$p.V^{\gamma} = constant \qquad (11)$$

With γ the ratio of specific heats c_p/c_v = 1,4 for air. It can be seen from the figure 4 that along with the pressure, the temperature rises. The compression work can be calculated as

$$W_c = -\int_1^{2'} p.dV = \frac{p_1.V_1}{\gamma-1}.\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad (12)$$

The state 2’ is the one after adiabatic compression, so at the right hand side of the horizontal line. For a compression to 10 baro that is 0,069 kWh/m³ (248 kJ/m³). But the air reaches a temperature of about 300°C. As it loses heat and cools down, some extra work has to be delivered to avoid the pressure going down. That is what happens on the horizontal part of the orange line 2’-2: isobaric cooling. This is also taking place in the aftercooler of standard compressors. The work required here is 0,028 kWh/m³ (99 kJ/m³), given by $p_2.(V_2-V_{2'})$, with $V_{2'}$ the volume at the right hand side of the orange line. The heat that is lost in this phase is 0,080 kWh/m³ (287 kJ/m³), given by $c_p.(T_{2'}-T_2)$. But regardless the heat that is lost, the total amount of work is 0,097 kWh/m³, which is 43% more than in the isothermal case.

Similar formulas count for adiabatic expansion, which is the blue line (2-3). If no heat is absorbed from the surrounding walls, the air cools down to about -125°C, setting free only 0,035 kWh/m³ of work in return (125 kJ/m³). So the round trip efficiency in an adiabatic system is as poor as 36%.

This is why compressed air has a bad reputation as it comes to energy efficiency.

In practical compressors the numbers are a bit more complicated. Oil free screw compressors are built as two stage machines, so with two screws, and with an intercooler between the two stages, sticking a bit closer to the isothermal line. But a temperature of the air before cooling is still about 130°C or higher. Oil injected screw compressors are normally single stage. They have the advantage that the oil can take some of the compression heat in the compression chamber, keeping the temperature down to about 100°C. But the oil has to be filtered out, which costs some energy, and which is not always 100% reliable. That is why water injected screw compressors are developed now. Finally, the most efficient compressors nowadays are the largest ones : turbo-compressors. They are built with 3 stages delivering an air temperature of about 100°C before cooling.

A compressor/expander with in process heat exchange

So what could an isothermal compressor look like when simultaneously it has to exchange as much Joules of heat as the Joules of shaft work that is delivered to the air ? How can the heat be taken out in the compression process, rather than afterwards ?

The following compressor sketch shows much of the characteristics of a heat exchanger :

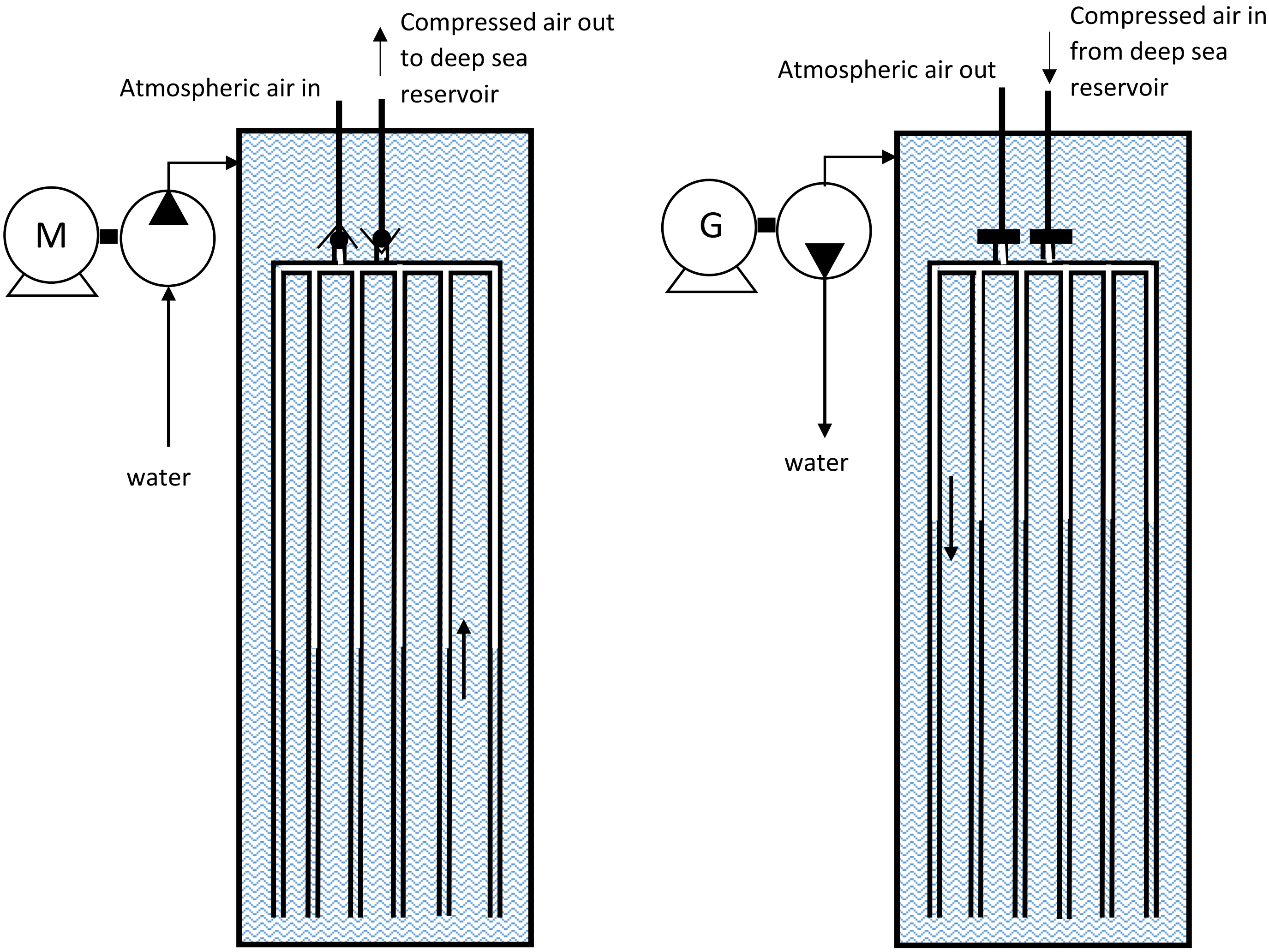

Figure 5 – Isothermal compressor (left) and isothermal expander(right)

As the water is pumped in the system, the air in the bundle of tubes is being compressed, and cooled at the same time. The air is finally driven out of the system via the non return valve. Once the water has reached this non return valve, the complete system is filled with incompressible water. The water can even be pumped a little over the non return valve to avoid that any dead volume of air is left behind. The pressure in the water can then be released without any significant energy loss, because it is incompressible. At that moment the non return valve towards the reservoir will shut off. The pumping can be reversed, taking the water back, sucking fresh air in.

A similar concept can be used as an expander. In that case, the non return valves have to be replaced by valves that can be switched actively. The pump becomes a water motor, and the electrical motor becomes a generator. A well defined volume of compressed air is given access to the system by the valve. Then it shuts off, and the air expands, pushing the water out of the system and taking heat from the water. When the air reaches atmospheric pressure, it can be filled again with water at atmospheric pressure, and the expanded air is released to the atmosphere by opening the air exit valve.

This concept is a particular execution of a so called "liquid piston". Indeed the water acts as a piston to compress the air. The many tubes offer more heat exchange surface, as if it were a real heat exchanger. Some of the studies on liquid pistons and isotheral compression will be addressed below. But first a better understanding of the potential of this concept is highlighted.

- It is interesting to know that this type of compressor / expander is not leaking air. Even if it is stopped halfway the stroke of the water, there are no gaps that make the air escape, as is the case with normal compressors. The pump may leak slowly when it is stopped. But a non return valve just behind the pump could prevent that. So in times of low wind energy the system could be operated at low power, pumping slowly, or pumping with short intermittent periods.
- As the pressure in the compression reservoir is isostatic in the liquid phase and the gas phase, the pipes inside this reservoir can be made thin. They don't have to hold any pressure differnetial. Conducting the heat is their only concern.
- What will be the temperature change of the process water during compression ? It was demonstrated earlier that it takes 0,067 kWh of shaft work to isothermally compress 1 cubic meter of air to 10 baro. It was also shown that 0,067 kWh of heat has to be taken out of the air during isothermal compression. What comes instead of the air in the system is 1 cubic meter of water. It can be calculated with $\Delta Q = m_{water}.c_{water}.\Delta T$, that this 1 cubic meter will have a final temperature change ΔT of less than 0,1°C if it absorbs this 0,067 kWh of heat. The specific heat of water is about a factor 4 times bigger than the specific heat of air. That is already advantageous. But the mass of 1 cubic meter of water in this formula (about 1000 kg) is reducing the ΔT significantly. Water is much denser than air and can absorb much more heat without getting much hotter.

This shows that if the sea would be used as a heat sink during compression or as a heat source during expansion, there is no danger for too much temperature change of the sea. And the size of the sea as a water reservoir is enormous.

It was explained earlier that during isothermal compression the internal energy of the air is not changing. In fact, what can be said now is that energy is not really stored in the air, but rather as heat in the sea. The air is only the energy transformation carrier. Yet, this air has to be held in a reservoir in the mean time, as it has been compressed. But the water is the real energy reservoir, storing and releasing heat, without hardly changing temperature though.

Park et al. [2] have shown that a liquid piston should work slow enough, as heat exchange takes time. In their proof-of-concept a liquid piston is used without the bundle of pipes, so there is less heat exchanging surface. But still it is correct that the cycle frequency of the system shouldn't be too high. This implies that, if the technology has to be scaled, large liquid pitons are needed that can work slowly, but still with massive hydraulic water flow to reach a high power level.

Heidari et al. [3] have studied the heat exchange more in detail. They claim that most of the heat transfer has to take place at the end of the liquid piston stroke. As for isothermal compression the instantaneous heat exchange has to follow the work added at that very moment, a plot of the work as function of the stroke (or the volume) proves this (figure 6) :

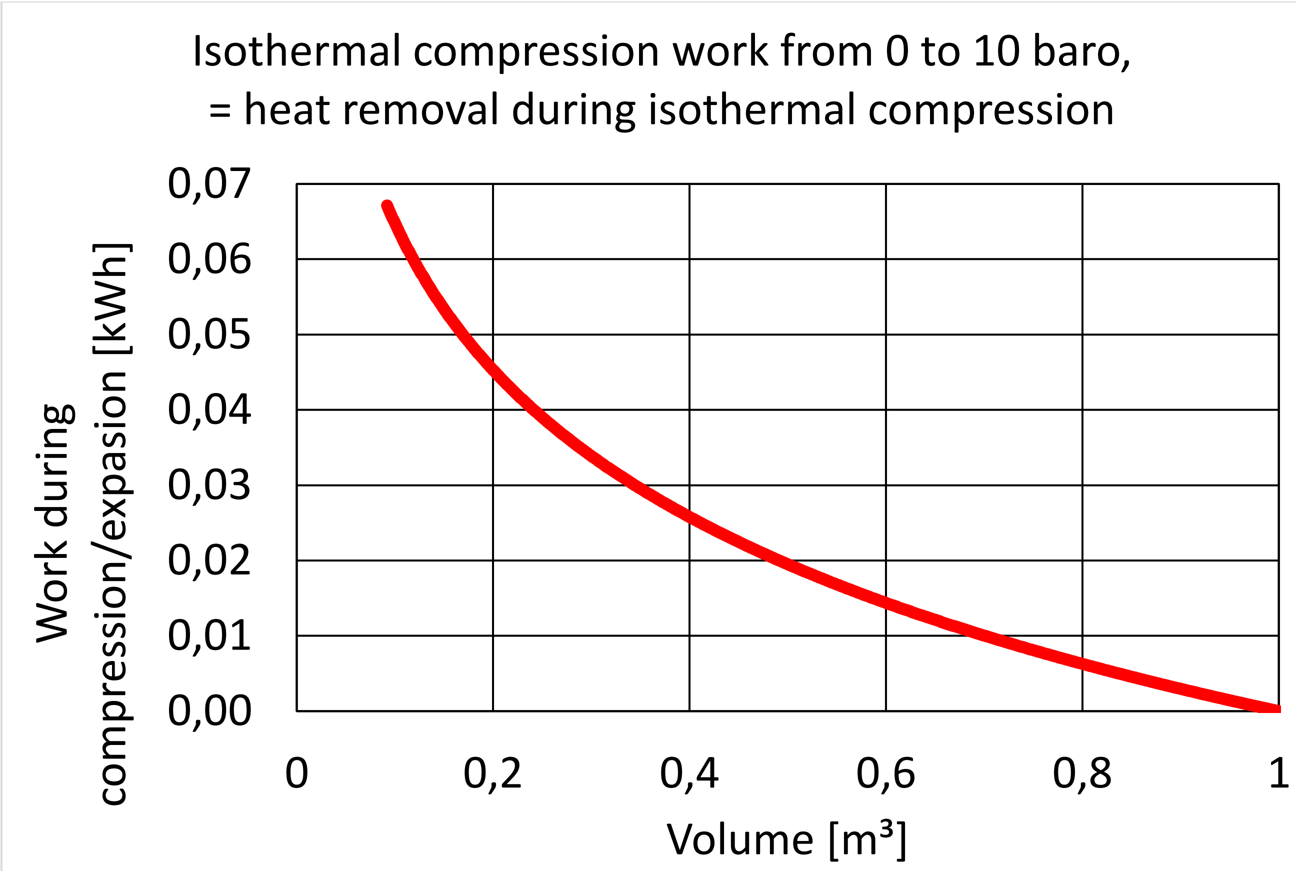

Figure 6 – Work for one stroke of isothermal air compression/expansion, also equal to the heat exchange

The left hand side of the curve will even become more steep if higher compression ratios are desired.

So in order to have better heat exchange at the end of the liquid piston stroke, Heidari et al. propose a concept that improves convective heat exchange at the end of the pipe bundle.

Another possibility is to have the pipes split in Y-branched towards the top, with smaller diameters at every split. That way the heat exchanging surface gets larger, improving the heat transfer.

However, the next section explains that there are other issues. The solutions for these other issues may also minimize the problem of the heat transfer at the end of the compression.

Power balancing of the isothermal compressor/expander

Imagine a pump with a constant flow of water, filling the liquid piston with its internal pipe bundle from figure 5. As the pump starts to fill the compression chamber, the work it has to deliver is almost zero. The compression chamber fills constantly due to the constant flow, and the pressure rises. But that pressure rise goes rather nonlinear (figure 4). And so does the work for the pump (figure 6). This is an unbalanced power situation. It is very uncomfortable for a wind mill or any other energy supply system.

A proposal to reduce this unbalance could be to operate several compressor chambers simultaneously, but each of them shifted in time. What does the power unbalance look like for a system of 6 compression chambers, with 6 pumps, each of them cycling at a period of 10 seconds, but with a time shift of 10/6 seconds between each of them. This example was worked out for a compression chamber of $1m^3$. The volume change of every chamber due to the pumping is given by figure 7, showing that the compression goes slower than sucking in fresh air after compression.

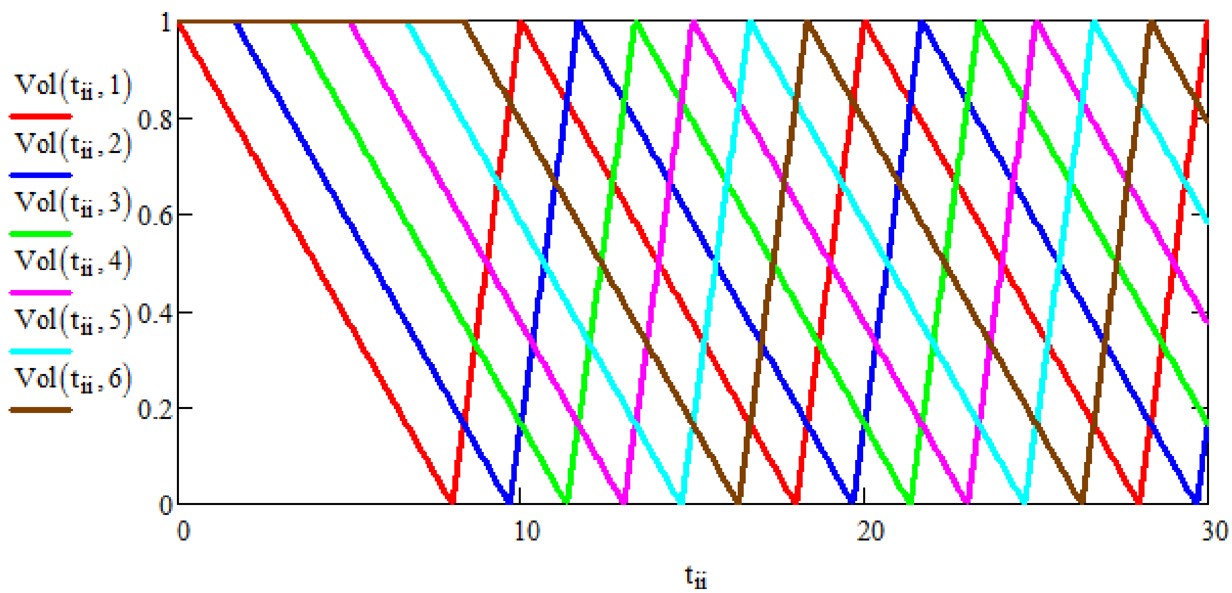

Figure 7 – Volume change in six air chambers of $1m^3$, with a period of 10 seconds, and 10/6 second shifted in time. Compression at constant water flow.

If the system is started with an empty reservoir at 100m deep, at first the pipes towards the reservoir have to be filled with air. So this is how the pressure build up looks like for all 6 pistons : figure 8

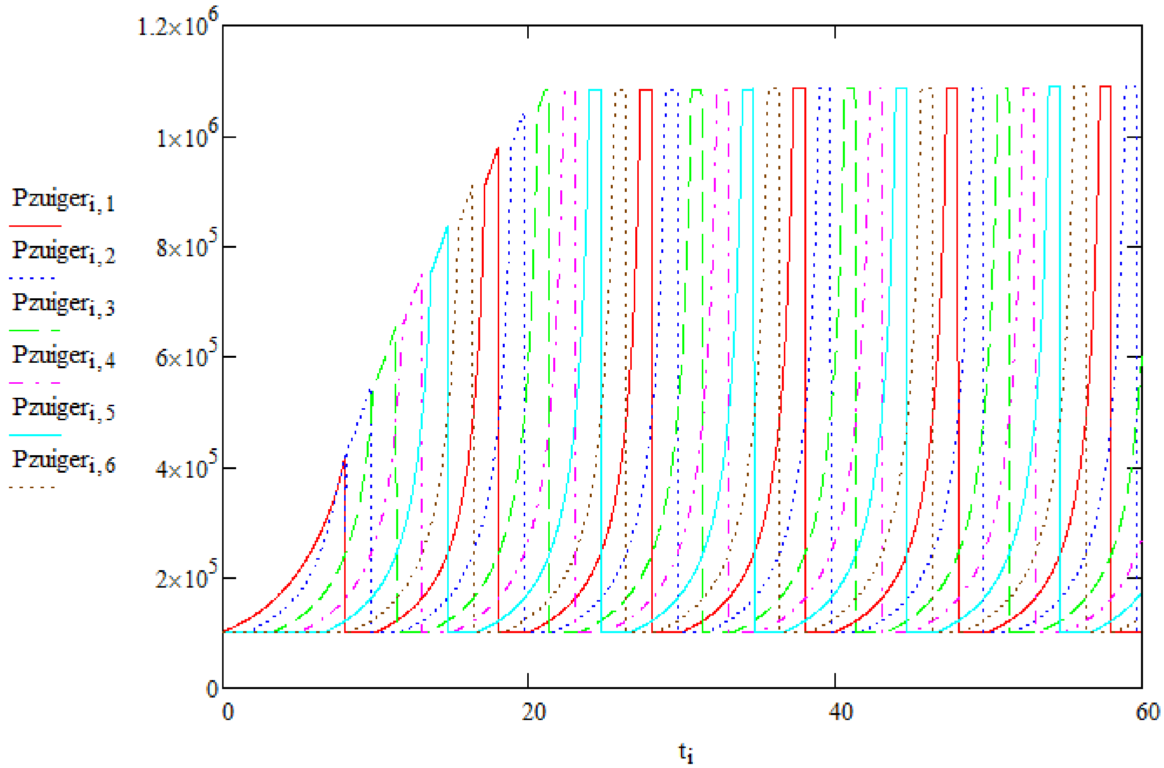

Figure 8 – Pressure evolution in 6 air chambres, feeding compressed air to an under water reservoir 100m deep. Compression at constant water flow.

The pressure in the deep water reservoir builds up is given in figure 9

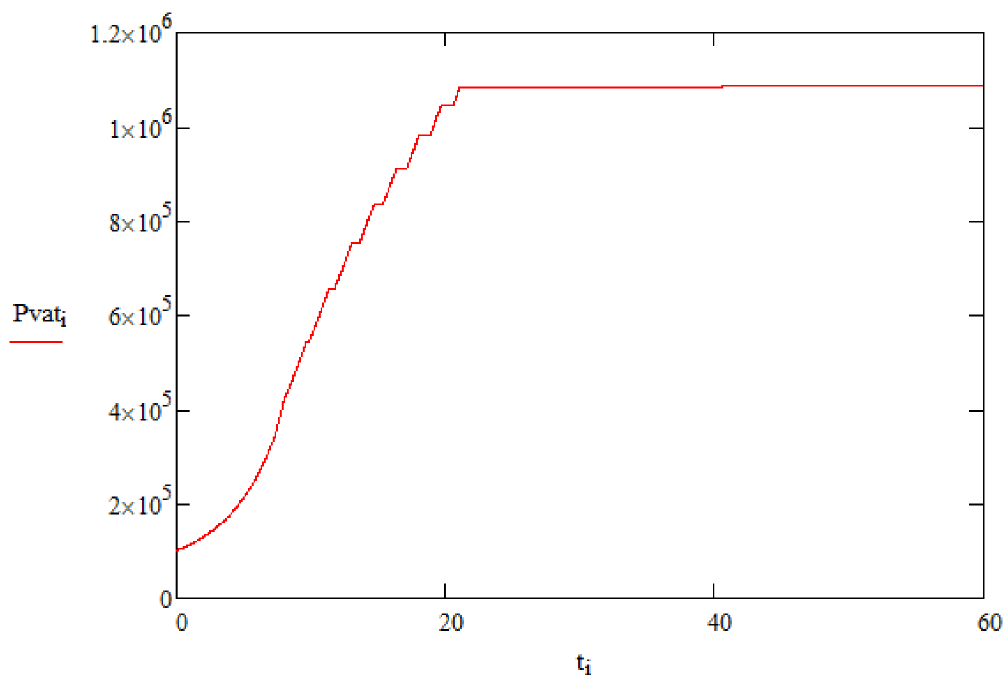

Figure 9 – Pressure build up in the under water reservoir, 100m deep.

Once the pipes towards the deep water reservoir are pressurized, the pressure stay almost constant.

Figure 10 is a graph of the power: the blue line gives the power of the first of the six compression chambers. The red line is the cumulative power of all six chambers.

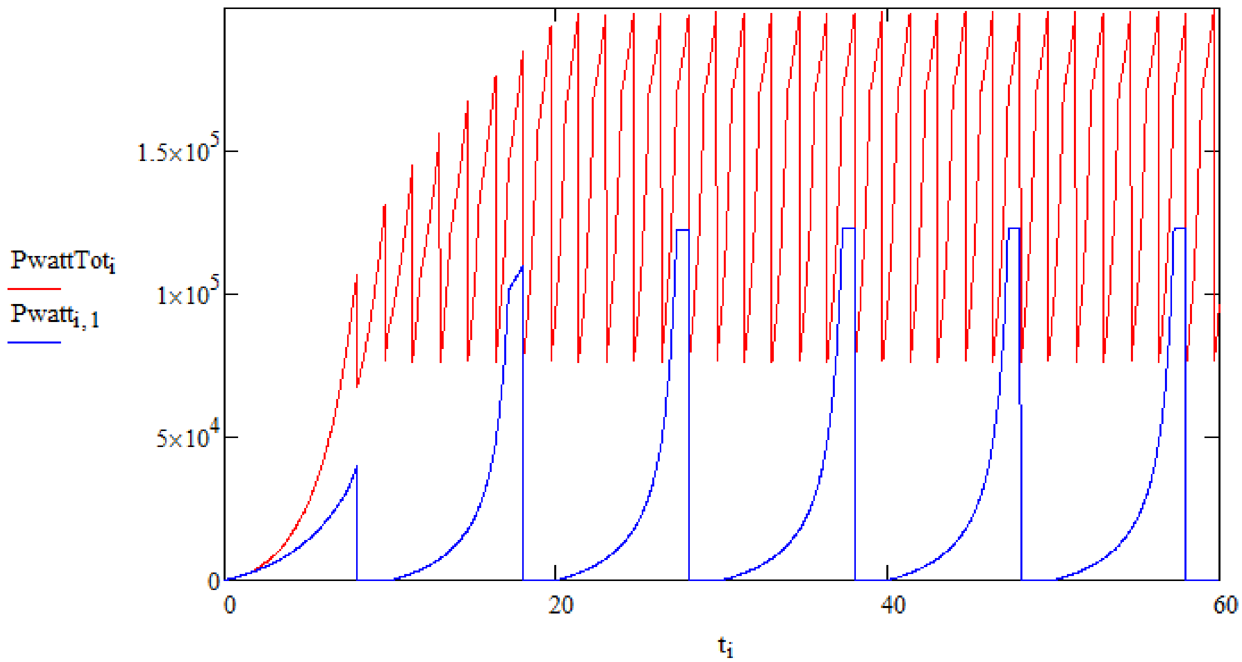

Figure 10 – Power of one pumping system (blue curve), and cumulative power of 6 pumping systems shifted in time with constant flow pumping (red curve)

It is very clear that even with six phase shifted systems, the power is still very much unbalanced. And this is only for a system at 100m deep, so with only 10 baro more or less. For higher pressures it gets even worse.

Can the power shown in the blue curve not be balanced in the first place ? That is the power curve of a single piston. If the power of each of the 6 pistons could be smoothened, so will also the cumulative curve of all 6 pistons.

The solution to this problem is to use variable flow pumps, so driven by a variable speed motor. In the most basic execution that could be changing the pump flow stepwise, or even switching to different pumps. At low chamber pressure the power can be pulled up by high flow pumping. Conversely, at high pressure low flow pumping is advantageous to balance the power.

The power of a hydraulic pump $P_{hydraulic}$ is given by the formula

$$P_{hydraulic} = volumeflow\,.pressure = Q_V.\Delta p = Q_V.(p - p_{atm}) \qquad (13)$$

With this formula, the power balancing can be refined. Here is the procedure. The volume flow can also be written as

$$Q_V = -\frac{dV(t)}{dt} \tag{14}$$

On the other hand, for isothermal compression the pressure p as a function of the volume is given by the ideal gas law

$$p = \frac{m.R.T}{V(t)} \tag{15}$$

The claim for constant power can then be written as

$$-\frac{dV(t)}{dt}.\left(\frac{m.R.T}{V(t)} - p_{atm}\right) = P_{hydraulic} = \ constant \tag{16}$$

Or written in another form :

$$\frac{dV(t)}{dt} = \frac{P_{hydraulic}}{p_{atm}}.\frac{V(t)}{V(t) - V_0} \tag{17}$$

V_0 is the initial air volume in the chamber.

This is a first order nonlinear differential equation. The left hand side of it is the volume flow of water that is needed to get a constant power for the pump. It can already be seen that there is problem at start, when V(t) = V_0. Then the denominator is zero, and the flow is supposed to be infinitely high. That is impossible of course. This was also obvious from the fact that the pressure at start is 0 baro. If no pressure is present, no power can be exerted.

Still it is interesting to solve the differential equation. How the results can be exploited is explained below.

There is an analytical solution for (17), but it cannot be written explicitly in V(t). Here is the result :

$$\frac{V(t)}{V_0} - ln\frac{V(t)}{V_0} = \frac{P_{hydraulic}}{p_{atm}.V_0}.t + 1 \tag{18}$$

If the volume at a certain time t is desired, the root can be found with numerical techniques.

The pumping can be done in 3 steps now :

1) At first, the volume flow of water should be infinite in theory. That is impossible, so it is set at its maximum, constant in time.
2) As the volume V(t) decreases, so will the theoretical value of the volume flow according to formula (17). So as the value from that formula reaches the maximum feasible pump flow, the pumping regime is switched to variable speed pumping, according to formula

(18). This phase starts with the maximum flow, but it will decrease now as time passes by.

3) Once the pressure in the chamber has reached the reservoir pressure, the pressure will no longer increase. Continued pumping will only result in driving the compressed air to the reservoir, at almost constant pressure. So in this regime a constant power is obtained by pumping at a constant flow too. The magnitude of this volume flow can be chosen the same as the one where phase two ended.

After these 3 regimes, the compression chamber is full of water, and the emptying at atmospheric pressure can be started.

The time of one such cycle can be controlled by the value of $P_{hydraulic}$. It is the desired constant power that was chosen. For high pumping power, a short cycle time is obtained, for low pumping power, a longer cycle time is obtained.

Here are the graphical results of the exercise. Again 6 pistons are used, each of them shifted in time 1/6th of the cycle time. The value of $P_{hydraulic}$ was chosen to get the same cycle time as in the previous example.

The 6 volume changes as a function of time are shown in figure 11 :

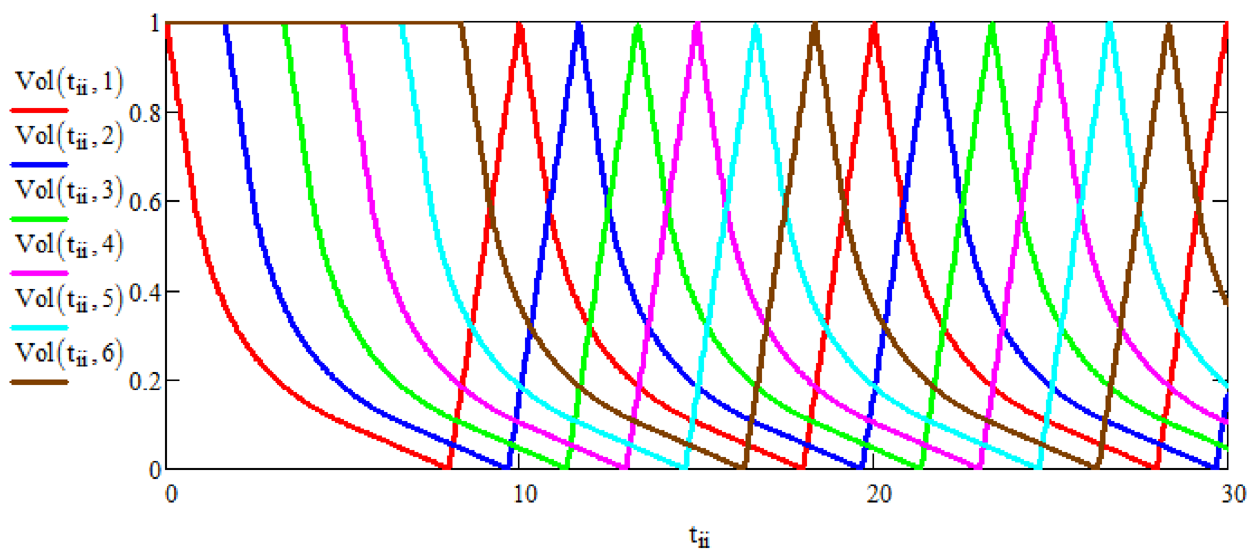

Figure 11 – Volume change of 6 time shifted air chambers, optimized for almost constant power compression

The pressures in the 6 chambers look like this :

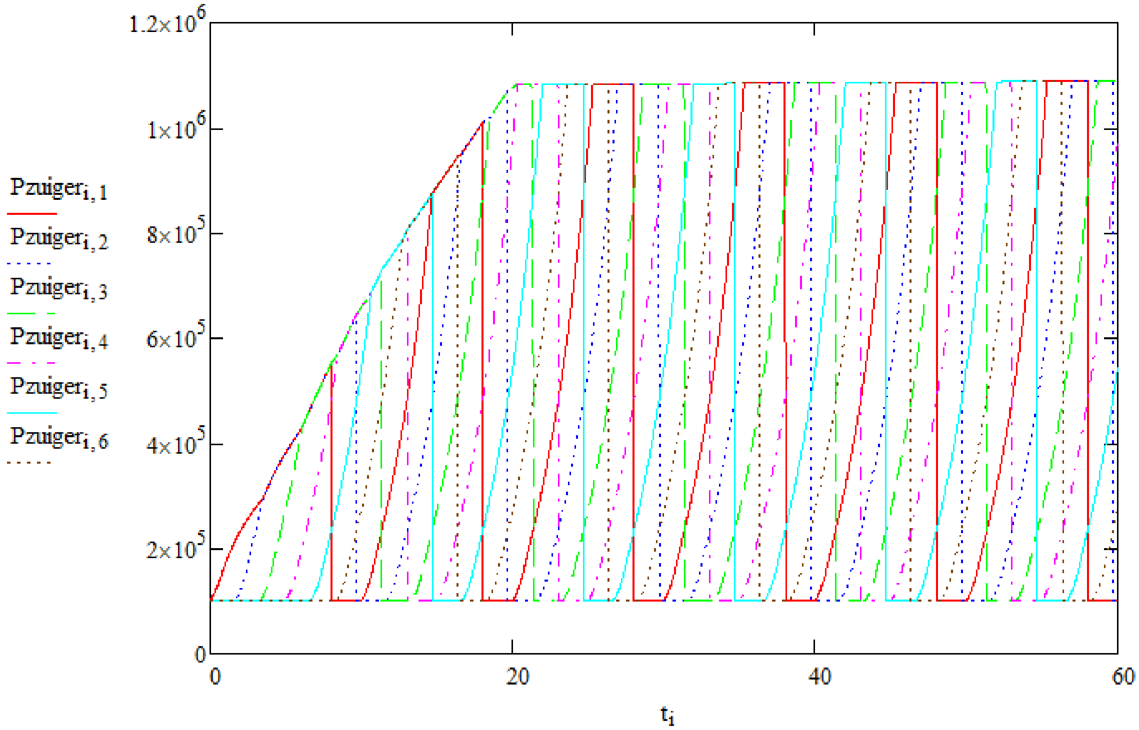

Figure 12 – Pressure evolution in 6 time shifted compression pistons, optimized for almost constant power compression

The reservoir pressure build up, starting from atmospheric pressure is given by figure

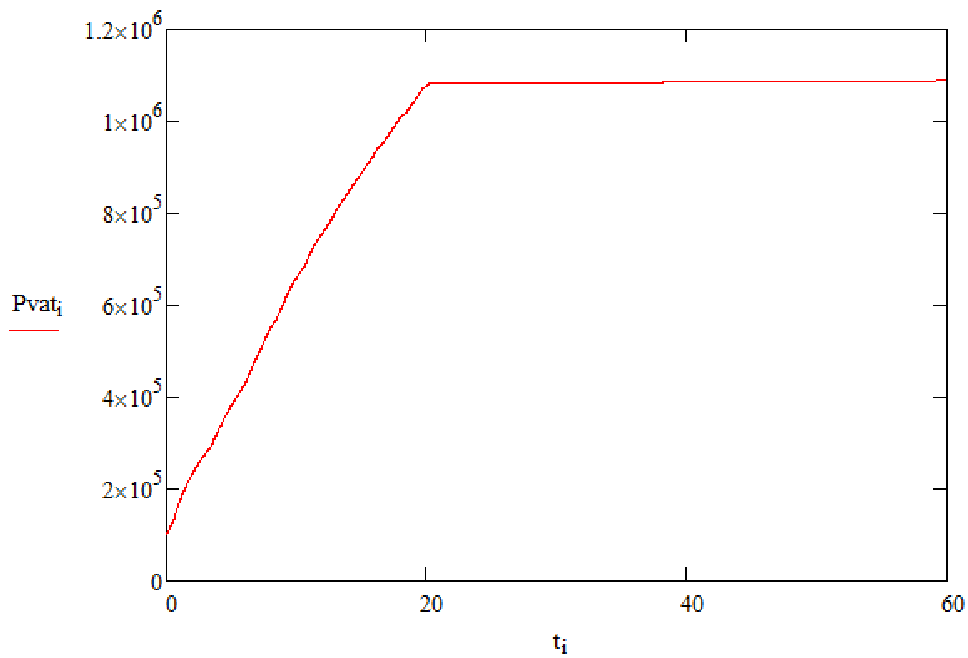

Figure 13 – Reservoir pressure during start up for almost constant power compression

And finally the power curve for the 6 pumps (red) and of one individual pump (blue) is shown in figure

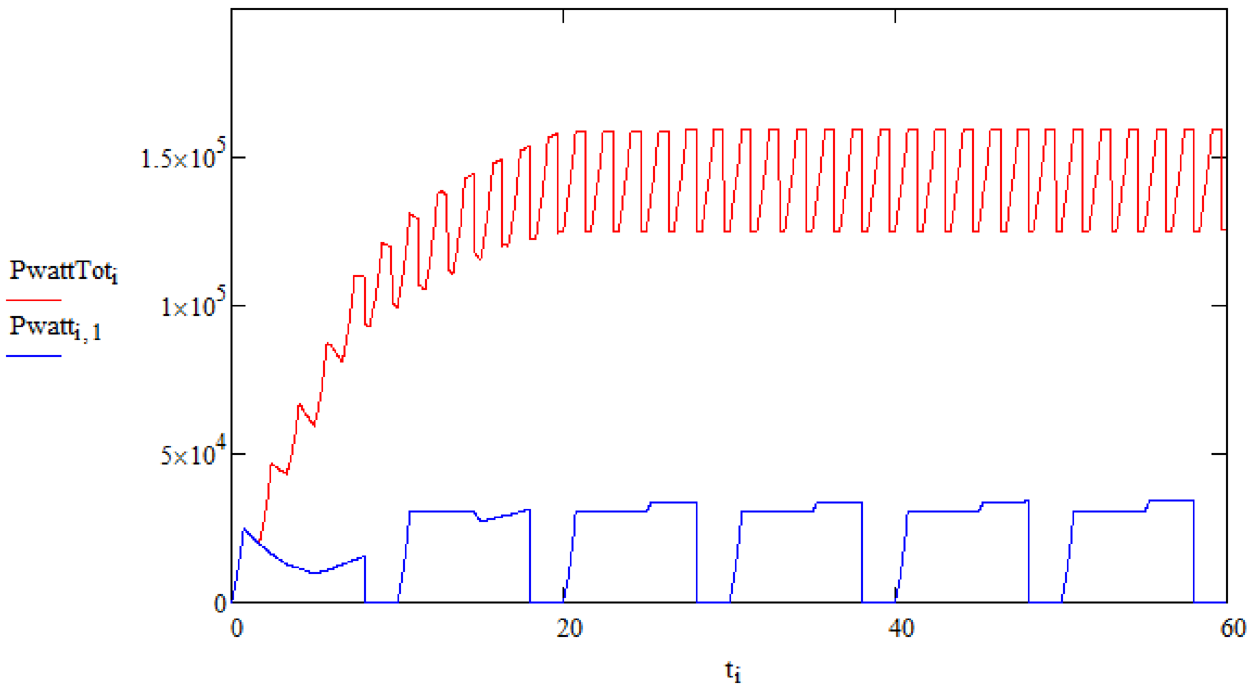

Figure 14 – Power of variable speed pumps, a single pump (blue), and 6 time shifted pumps cumulative (red)

It can be seen that the blue curve is almost flat during compression, apart from the first few strokes at start up. The cumulative curve has improved a lot too. However, it is astonishing that even with 6 time shifted pistons the curve remains spiky. If more compression chambers and pumps are used it gets better, as is shown below for 8 phase shifted pistons working in the same pumping regime.

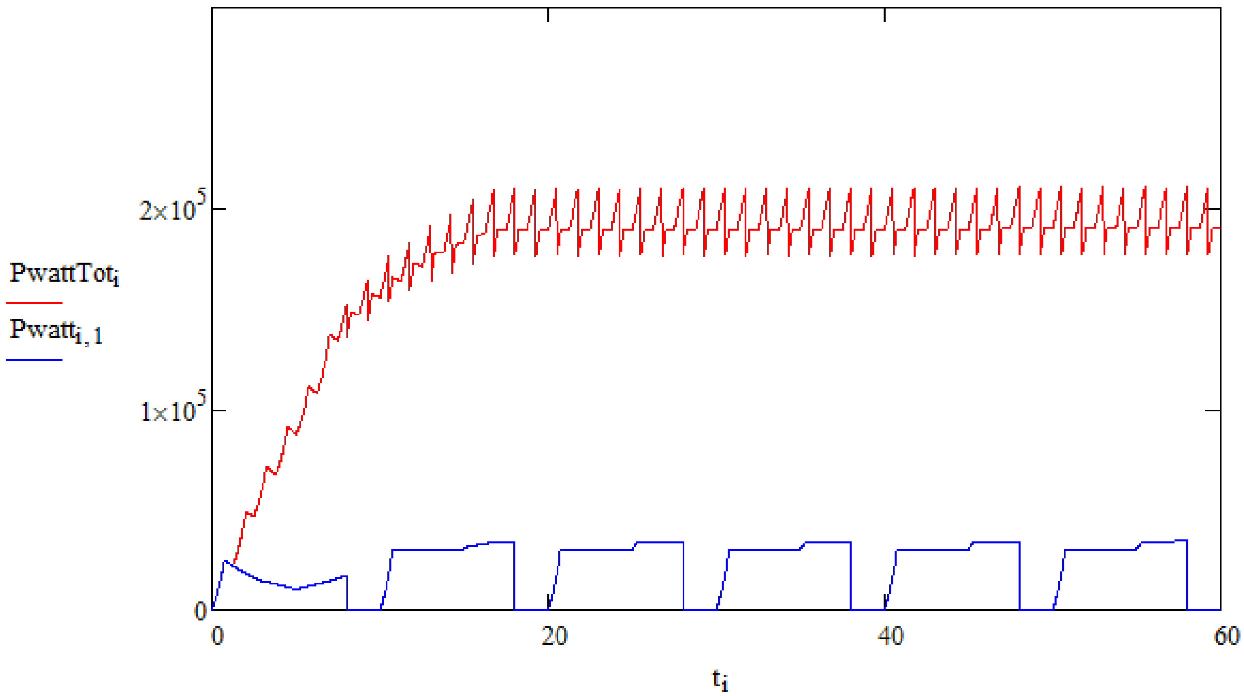

Figure 15 – Power curves for a system of 8 time shifted compression systems. Power for 1 of the eight compression chambers (blue), and cumulative power for all 8 compression chambers (red).

Another way to reduce these remaining spikes is to shorten the time of emptying the compression chamber, unloading the water and sucking in fresh air much faster, if that would be possible.

And last, what this curve also shows, is the average working power of this system of 8 liquid pistons, each of them 1m³ large, operating in a 10 seconds cycle time, feeding a reservoir 100m below the water surface : almost 200 kW.

Conclusions of power balancing

From this analysis it can be understood that variable speed pumping is needed to smoothen the power. At the end of each compression the pumping should go very slowly. At the same time this is advantageous to have a better heat transfer. It was explained earlier that exactly at the end of the compression significantly more heat has to be transferred to assure isothermal compression.

On the other hand, at the beginning of the compression only a little heat has to be removed, but the water flow should preferably be as high as possible here. A suggestion for further investigation could be to replace this initial high flow water pumping by filling the compression chamber partially with compressed air from an ordinary blower with a pressure ratio of only 2 for instance. Not much cooling is needed at the start of the compression, (see figure 6), and this slightly compressed air can enter the chamber very fast.

General conclusions

In this study first a comparison was made of different energy storage techniques. For floating wind mills at deep sea, compressed air energy storage in deep water looks like an interesting solution that is scalable.

Secondly the importance of isothermal compression and isothermal expansion has been highlighted. A lot of energy gets lost if adiabatic conversion is used.

Finally an analysis is made of power balancing. The pressure varies so very much more at the end of the compression stroke, that specific measures have to be taken. A suggestion is made for further smoothening this power curve with a blower compressor at low pressure as a precharger.

What is not investigated in this study is how fine the bundle of pipes in the isothermal compressor/expander has to be designed to obtain excellent heat transfer. Another potential problem that was not addressed is the fact that the air could solved in the water, as is the case with CO_2 in sparkling water. To reduce that, little floating balls could be added to the water surface in the pipes. But it requires further investigation.

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