The Competitive Advantages of REHOS Technology

by
Johan Enslin

Heat Recovery Micro Systems

Heidelberg
South Africa

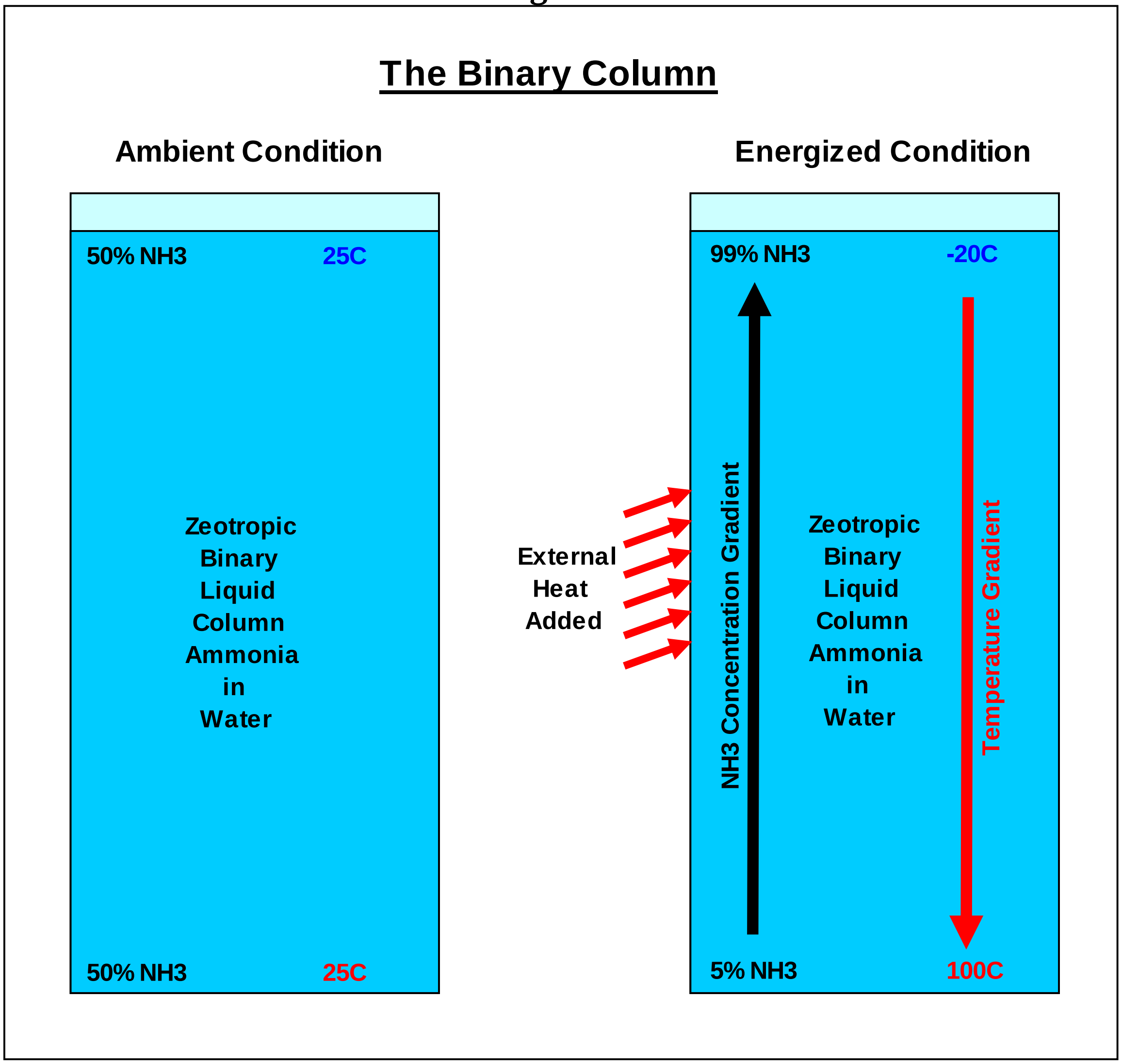
Introduction:

REHOS Technology, as well as costing methodologies, was already comprehensively described in several documents (see publications at the end of this paper), but it is required to evaluate this revolutionary technology against existing competitive state-of-the-art technology. This document therefore try to compare the REHOS technology with rival developments, and not to describe the REHOS functions, as this was already done.

Summary of REHOS concepts:

The heat of solution (HOS) concepts all stem from the physical characteristics of a zeotropic binary mixture in the vertical column reactor. This is sketched in Figure 1 below and the sketch accentuate the binary mixture reaction with heat added. On the left is the column at ambient conditions, with the 50% ammonia in aqua mixture filling the complete length of the column.

Figure 1



As soon as external heat is supplied to the column, the mixture react by creating an ammonia concentration gradient with the higher NH3 concentration moving to the top of the reactor while the higher density, hotter, but leaner NH3 mixture migrating to the bottom of the reactor. Simultaneously the mixture migrating to the top of the reactor is cooled while the reactor bottom is heated, creating a temperature gradient with the hottest area at the reactor bottom. Heat energy is required from external sources to establish this concentration and temperature gradient, but once established, the external heat source may be removed and the gradients would very slowly dissipate as heat is lost by radiation out from the hot bottom, as convection is inhibited due to density differences.

Figure 2

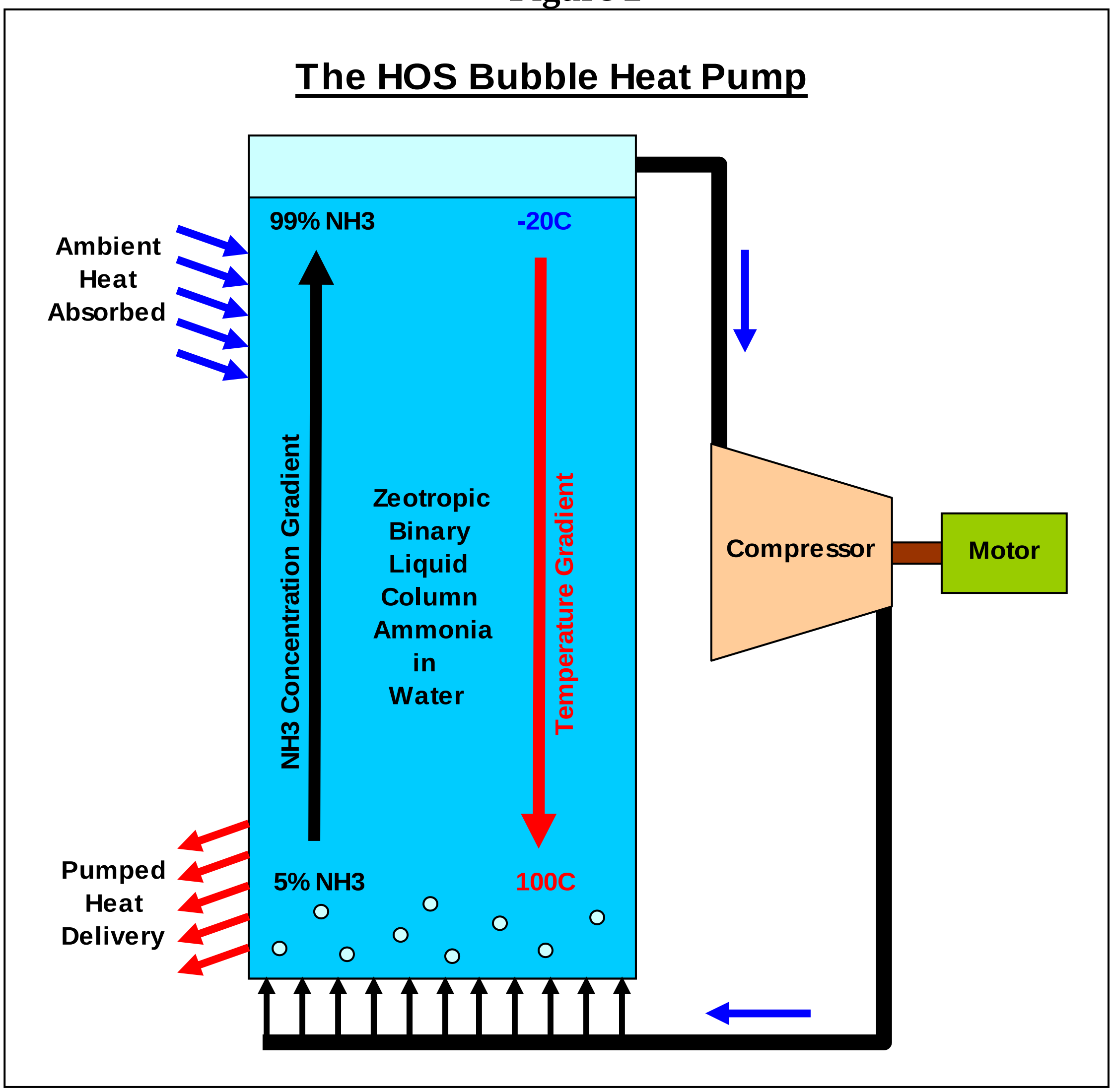
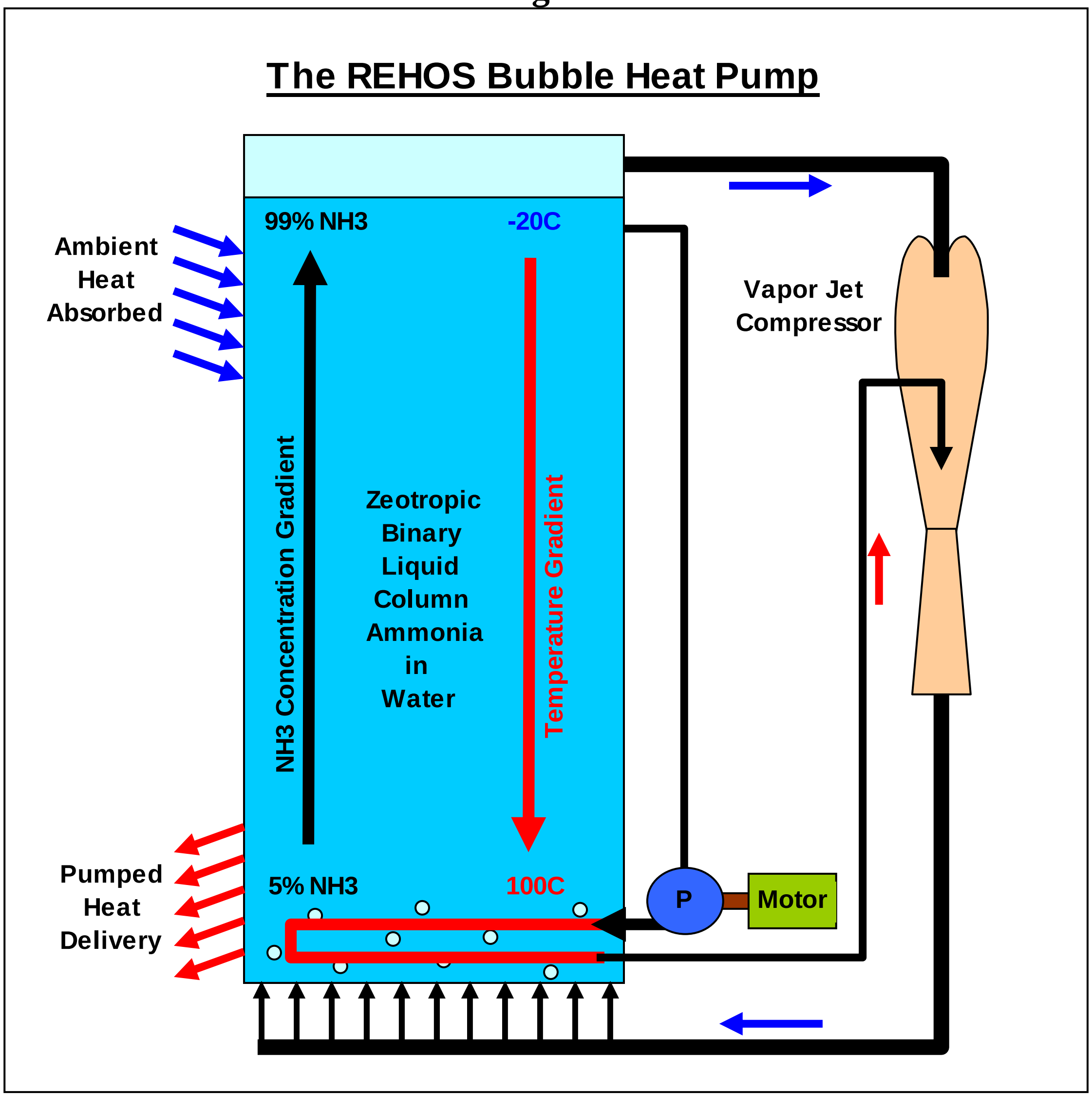


Figure 2, above, sketch the HOS heat pump. The coefficient of electrical performance (COP_e) of this type of heat pump is very high (it also use heat to power the heat pumping process, and not only electricity), as the compressor pressure ratio (and therefore temperature increase with pressure), is very small. The compressor only need to provide enough pressure to overcome the liquid column hydraulic pressure created by the gravity force on the liquid column. With the column height fixed, this hydraulic backpressure is fixed, and with the column mixture operating at the temperatures as shown, the compressed vapor temperature only increase about 2 - 4°C, making the heat pump COP_e easily go to about 50-100, which is a factor of at least 10 x the performance of a conventional vapor compression heat pump which would have given a COP = 1,7 (as it only use electricity to power the process) for the same temperatures. This give the **HOS heat pump an electrical performance of ~ 50 x the conventional vapor compressor type heat pump**.

The REHOS type heat pump simply replace the motor driven isentropic compressor with a vapor injector type compressor, using regenerative heat of absorption of the vapor bubbles at the bottom of the reactor to evaporate the pumped, high pressure liquid in a

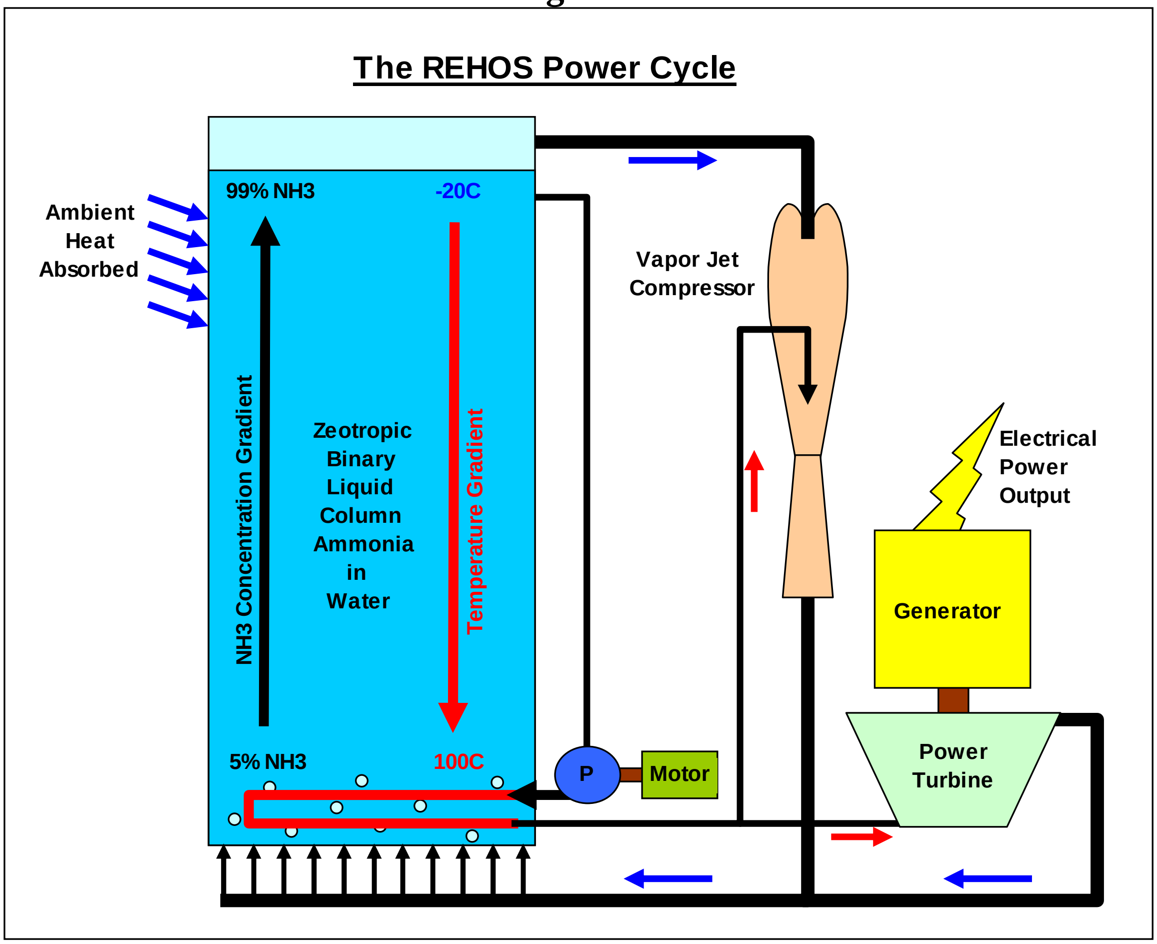
Figure 3



heat exchanger positioned in the hot bottom of the reactor. This injector type of compressor therefore use a very small amount of electrical energy to only drive the liquid pressure pump. The REHOS type heat pump COP_e is therefore a factor of 5 x the HOS heat pump performance, putting it's electrical performance into the range of COP_e = 500, or a factor of **~ 250 x the conventional vapor compression type heat pump.** More detail in the publication [8] to better understand the large numbers.

The REHOS power cycle sketched in Figure 4 below, differ from the REHOS heat pump only in the removal of a heat output, and use of the pumped heat energy to evaporate a lot more liquid, to power a vapor expansion turbine to generate power. The low pressure exhaust of the turbine adds to the compressor output vapor, to be regeneratively re-used in the reactor bottom for the evaporation process. The **REHOS power cycle therefore have a heat to electricity conversion efficiency of 80 - 90%**, making it the ideal low temperature waste heat to power energy recovery machine. This high efficiency is properly explained in other papers like [7], [8] and [9], confirming that no thermodynamic laws have been violated!

Figure 4



Environmental heat can be extracted from the environment, as the cold end of the reactor operate at some 20°C below zero. A simple liquid-liquid heat exchanger can therefore extract ambient heat from water sources like rivers, streams, dams, lakes and the sea to generate power from at the revolutionary high (> 80%) cycle efficiency!

Extracting heat from a liquid like water, has a very high power density due to the large medium density and sensible heat content of the water. The heat exchanger to do this is therefore small and cheap, while extraction of heat from the air has a much lower density and heat capacity. The heat exchangers are therefore much more bulky and expensive. In cases where very small amount of power would be required, it would be practical, however, eg. when you adapt a bicycle to use the thermal energy in the ambient air to deliver the required 500W to 1 kW power using a REHOS cycle, revolutionizing personal mobility in very poor communities in Africa, India not to forget India and Japan etc.

REHOS vs Vapor Compression type Heat Pumps:

In warm climates a very large percentage of electricity use actually go towards air conditioning and refrigeration. Should the standard vapor compression type heat pumps used in air conditioning and refrigeration be replaced with HOS type heat pumps, the power consumption in this segment of the economy would drop by a whopping 98%, as the COP_e values of the HOS heat pump calculate to ~ 50 x the normal VC type, and would therefore have an electrical energy consumption (ignoring thermal energy used) of 1/50 th (or 2%) of the current A/C consumption!

Using the REHOS type heat pump, would see the air conditioning and refrigeration power consumption drop to less than 1% (about 0,4% or 1/250 th) of what it currently is.

Energy used for air conditioning and refrigeration is said to be ~ 40% of the total power used in Mumbai, India, while Saudi-Arabia dedicate some 50% of their total electrical power used in summer, to air conditioning. Even Britain use some 20% of the power generated for air conditioning and refrigeration according to some sources. Due to global warming effects it is said that Europe would increase the energy used for air conditioning by 72% in the next 15 years, so the forecasted demand for REHOS Technology is extremely high!

Using such low-powered heat pumps to cool air to below zero to extract water vapor from the humidity in the air would only (just about) cost the fan running cost to move the large mass of air through the heat-exchanger. The water so generated from the air could therefore be priced at a small fraction of municipal water current costs, putting an immediate stop to other much more expensive desalination technologies used to supplement potable water. See the example mentioned in [8] and repeated in [10]. On a large scale REHOS heat pumps could produce all the agricultural water requirements for irrigation and farm animal consumption, possibly even powered by the wind, replacing the traditional windmills driving borehole pumps.

REHOS heat pumps would be able to provide water to everybody across the globe, to eradicate drought effects, even in harsh environment places on earth. Providing water to drought-prone area's would also increase the vegetation in these area's to absorb more CO_2 across the globe!

REHOS vs Hydro Power:

A pool of water absorb heat from the sun, so it actually form a thermal energy storage facility. Should a REHOS cycle be installed to generate power from the stored solar and environmental thermal energy in the water in the pool, the water would cool down below ambient, absorbing heat not only from the sun, but also the rest of the environment, like the earthen walls and bottom of the dam, and air flowing over it. As energy storage medium the efficiency is very high, close to 100%, as any heat used for power, lower the water temperature, blocking heat loss and in fact accelerating ambient heat (waste heat) inflow from the environment.

This power from the thermal energy in a water pool, compete very well with hydro power, as both can deliver power on demand, dispatchable, but the environmental impact of a large dam, as well as the huge civil construction make the hydro-power installation a lot more capital intensive. The low cost, extremely scalable base load **REHOS pond power generation** with a capital investment around 1550 $/kWe may provide power at a cost of < $0.03 /kWh (targeting $0.015/kWh) to very small users (see [1] and [2]), like single households from a swimming pool, or hotels and buildings from larger, man-made solar absorber pools, outperforming the larger, more capital intensive hydro power generation.

REHOS vs Solar PV power:

Solar PV power have mainly 2 huge problems. The first being the intermittency, delivering power only when the sun shine. Even dark clouds casting shadows over PV panels cut the power produced. Although the capital investment is relatively low (~ 1220 $/kWe), it really cannot compete against base load power generation, unless energy storage is implemented with the PV. Current storage cost, however, is ~ 200 $/kWh heading for a possible 100 $/kWh in the next 5-10 years. This, however, increase the cost to at least 3020 $/kWe, which is well above the **base load REHOS pond cost**, and disqualify the solar PV therefore completely on price.

The second huge problem is large solar collector area used for generating power. PV panels have efficiency of converting solar energy to power ~ 20%, and access for maintenance dictate a certain spacing of panels, increasing the land requirement even more. With the low energy density of solar irradiation from the sun of ~ 2000 kWh/m2.annum it is therefore not a surprise that a fixed tilt PV installation delivering energy of 1 GWh/annum require 2,8 acres (11 311 m2) to achieve it. It boils down to an efficiency of ~ 4,4% of the solar energy is actually converted to electricity! Comparing this to the collector efficiency of ~ 100% for a REHOS pool (as explained above) and REHOS conversion of thermal to electrical efficiency ~ 80%, give and overall REHOS pond efficiency of ~ 80%, requiring only 625 m2 to deliver the 1 GWh/annum from the same solar irradiation.

The **REHOS pond type power generator only use < 6% of the land area** required by solar PV for the same energy delivered!

REHOS vs Wind Power:

Although wind power is low in capital investment (~ 1390 $/kWe), it suffer from the same intermittency problems like solar PV. It therefore also need energy storage to make it viable, out-pricing itself compared to the described base load REHOS pond generator.

The power density of wind power generators also need very large energy collectors, dwarfing the competition in the compact REHOS converter with a much smaller footprint for the same power output.

REHOS vs Solar Thermal (CSP):

Similar to solar PV installations, the solar collector area is very large for the energy produced, for similar reasons than the PV installations. A typical example is the Kaxu Solar One parabolic trough power station delivering 100 MWe. The trough collector field span 775 acres (3 136 290 m2), calculating also to a solar irradiation to power delivered efficiency of ~ 4%. In this case of CSP, the thermodynamic heat to power conversion efficiency of the rankine cycle is 42%.

The CSP installation is also a dispatch-able, base load generator, making use of thermal storage, but on the ground area used, it cannot compete with the REHOS pond generation. Also, on pure capital investment cost of 4336 $/kWe it is much more expensive than the 1550 $/kWe of the REHOS pond generation concept.

The REHOS cycle, however, does not necessarily have to compete with CSP. Where the investments have already been made in constructing the CSP plant, it does not need to be replaced, but a REHOS cycle add-on to re-use the waste heat dissipated in the cooling towers may easily double the CSP power output. This CSP re-powering would stop the investment from becoming stranded assets. As the rankine thermal to power conversion efficiency is 42%, the balance of 58% is currently rejected into the cooling water, dissipated in cooling towers. Without interfering into the current operation, the cooling water can be routed through a REHOS cycle heat exchanger, allowing a REHOS cycle generator to deliver another 80% of the wasted reject heat energy as electricity! **This would double the CSP-REHOS combined cycle power output**, and therefore half the electricity production cost!

REHOS vs Nuclear Power:

Nuclear power generation have the drawbacks of the safety issue, making nuclear installations much more capital intensive (5141 $/kWe) and the time for constructing nuclear plants are normally several years. It is therefore built for the real long-term, 60 years or longer. Nuclear stations smaller than about 100 MWe is therefore not practical. In these aspects, REHOS pool generation capital investment would be only 30% of the nuclear equivalent, may be scaled down to even a few kilowatt in size and can be built in a very short time. **Nuclear generation in this form, simply cannot compete.**

Similar to the arguments used in the CSP comparison, the nuclear final rankine power output cycle have a thermodynamic rankine cycle efficiency also ~ 40-45%, making the waste heat rejected into cooling water more than the electrical power produced by the station. Again, in already existing stations, like with CSP, without interfering into the current operation, the cooling water can be routed through a REHOS cycle heat exchanger, allowing a REHOS cycle generator to deliver another 80% of the wasted reject heat as electricity! **This would double the Nuclear station power output**, and therefore half the electricity production cost! This is a way to safeguard against the high capital investment of the nuclear station becoming stranded capital in the face of lower cost renewable generation.

In some countries in the colder northern parts of Europe, like Northern China, Russia and others, Nuclear reactors are also built specifically for district heating, delivering pure thermal energy at low temperatures into huge district heating distribution piping networks. These nuclear stations only cost 512 $/kW_th and are built smaller (like 50 MW) and shorter construction times as well. **Using a nuclear concept like this at a cost of only 10% of the normal nuclear power capital investment, producing thermal energy for conversion to electricity in a separated REHOS cycle power station at 80%+ efficiency, may produce real low cost nuclear electricity!**

REHOS vs Diesel/Gas Turbine Power:

Capital investment is low for gas turbines and power generation diesels (~ 680 $/kWe) but the fuel is expensive and make up the real electricity cost of produced power. The high cost of power produced from diesel or gas therefore warrant billions of dollars to be spent on R&D for improving the efficiency of diesel and gas turbine generators. Larger machines often warrant a bottoming rankine cycle added in the flue path of the diesel or gas turbine. Although this rankine cycle only have an efficiency of ~ 40%, the overall power station efficiency goes up from ~ 40% to about 60%, generating a tremendous fuel (cost of electricity) saving.

The REHOS cycle, generating power from the heat of some external combustion heat source, operate at 72%, assuming a combustion furnace efficiency of 90% and the REHOS cycle at 80%. This would topple even the best current combined cycles (64% from 9HA.02 GE gas turbine of 826 MW in 1 x 1 combined cycle configuration and aiming for 65% by 2020).

The alternative would be not to compete, but allow a REHOS cycle as add-on to the existing prime mover. With a modern supercharged, intercooled diesel giving 38% efficiency running its exhaust through a heat exchanger can, with REHOS, convert another 80% of the wasted, recoverable 55% heat remaining in the flue, to power, delivering a **Diesel-REHOS combined cycle (or GT-REHOS CC) with an overall fuel to power energy efficiency above 80%.**

REHOS vs Fossil Combustion (Coal/Oil) Power Generation

New coal power generators have a capital cost around 2950 - 3560 $/kWe and are therefore as investment ~ double the cost of REHOS pool type generation. Global warming effects have also lead to the boom of renewables and the pressure for the demise of fossil combustion power generation worldwide. The problem is, however, that ~ 80% of global power generation comes from coal fired power generators. What to do with these stranded assets? Some of these stations have just been built, having a usable life ahead of 50 years+. New capital must be found to finance the renewables, nuclear, geothermal, hydro etc. required to replace the fossil combustion units.

Obviously the REHOS pool type generation, CSP-REHOS and Nuclear-REHOS combined cycles can replace any existing fossil combustion plant with cheaper, non-carbon generation, but the **REHOS cycle is special, in that it can facilitate the gradual decarbonization of power generation globally**. Instead of simply replacing them, use REHOS cycle add-on as already described for the output doubling of CSP and nuclear power plants. Fossil generation all have rankine cycle efficiencies below 50%, rejecting the other 50% energy as waste heat into the cooling water and dissipated into huge cooling towers. Putting a REHOS generator in the cooling water line could produce as much electricity as the current generators, doubling the output (or rather, halving the fossil combustion and CO2 production while keeping the station output constant). With the station fossil side only producing 50% of the delivered electrical output, pressure can be reduced in the boilers to extend the life of pressure parts, avoiding the source of the most coal-fired station failures, namely tube leaks in the boiler. This way the national grid electrical infrastructure, transformers, power station operational infrastructure including operational staff are re-used, avoiding the total stranding of the power station as an asset to the utility. In due time as money allows, low cost REHOS pond generation can be built on the same power station location, gradually doing away with the requirement for coal combustion.

REHOS vs Diesel/HFO in Marine Propulsion:

Marine power systems used for ship propulsion are unique, in that water at ambient conditions are always readily available. Extracting large amounts of heat energy from the available water source using a REHOS generator would be logical. Delivering propulsion power at less than $0.03 /kWh with a REHOS generator extracting ambient heat from the water make a lot more commercial sense that paying $0.28 /kWh for producing the same power in a diesel or HFO combustion engine to produce the power. The low cost of the REHOS power of only 10% of the diesel equivalent is not the only advantage however.

Using the REHOS power unit, the propulsion system use solar environmental heat from the sea, and emit nothing. This is the greenest marine propulsion system possible!

REHOS vs Fuel Cells:

Fuel cells using hydrogen (H2) and air, have been technologically proven, and are now being used extensively for de-carbonization of the mobility industries. The power density of fuel cell power generation, with the H_2 storage containers, is much higher than current state-of-the-art battery energy storage like Li-ion batteries used for electric vehicles (EV's). Where current Li-ion batteries have a weight to power ratio of ~ 5-8 kg/kWh, the fuel cell power pack with fuel and containers have a ratio of less than 0,5 kg/kWh. New R&D for the mobility industry really focus on new Li-S batteries, with a promise of power density ~ 1 kg/kWh in a few years. This is currently experimental only. Electrical propulsion, however, is highly accredited for road vehicles, aero developments and even bicycles. Several commuter companies are developing passenger drone-type vertical lift transporter units, using Li-ion batteries, demonstrating the high control-ability of electrical propulsion. Battery operation for transport, however, has a range problem, as greater range tend to increase the battery mass to be carried, and therefore use more energy to propel this mass. Fuel cell power packs combined with batteries, however, make an excellent longer range hybrid vehicle, but, of course, need H_2 fuel distribution infrastructure to be developed.

Electrical propulsion in the aero-industry is in the process of really taking off, as large aeroplane manufacturers like Airbus and Boeing are developing electrical propulsion passenger planes, using hydrogen as fuel, producing propulsion electricity in fuel cell power packs. The power density of the fuel cell (with its H_2 fuel) is high enough to even use in a plane.

Currently **fuel cells suffer from two main drawbacks, namely the high cost** (which should reduce with time as mass production is developed) and the **low thermodynamic efficiency**. The best modern fuel cells operate at ~ 40% efficiency, also generating the balance of 60% as heat! Although this efficiency range in the same order as the traditional gas turbines that used to provide aeroplane propulsion, it is the largest limitation factor for the use of fuel cells, making the H_2 fuel containers larger, again limiting aeroplane range.

REHOS technology can come to the rescue for both drawbacks, however. H_2 combustion furnaces can very easily be made with fuel energy to heat efficiency > 90%, as the required heat would be low temperature < 100°C. Using a REHOS power generator to convert this combustion heat to power would render 80% efficiency, making the overall **Combustion-REHOS power pack produce electricity at ~ 72% efficiency. This is nearly double the fuel cell efficiency, at a fraction of it's cost!**

As explained above in the discussion on diesel and gas turbine combined cycles, the REHOS generator may easily be added onto existing fuel cells, to make use of the waste heat to produce the **FC-REHOS combined cycle, delivering electricity at > 80% efficiency!** This kind of power pack would break all current range limitations for road transport as well as aero-mobility applications!

Assisting to build the required hydrogen fuel distribution infrastructure, the low cost renewable REHOS pond generators operating across the globe at generation cost of < $0.03 kWh, may be built to produce electrolytic H_2 from water at small and large scale. Storage of this H_2 energy may be in the form of ammonia (NH_3) plants producing ammonia from H2 and air, also for energy export. Currently ammonia plants use ~ 12 kWh/kg NH3 produced, but this is lowered substantially through R&D in this field. Energy storage density using H2 bound to chemicals like nitrogen (NH3) or organic molecules like Marlotherm SH, produced by Sasol as thermal storage & transfer oil $(C_{21}H_{20}) <=> (C_{21}H_{38})$ is much higher than compressed hydrogen, and can be stored at much lower cost containers where power to weight ratio is important.

REHOS technology can really enable and revolutionize the Hydrogen Society!

Application where the REHOS Technology can be introduced to revolutionize our lives in the global community is absolutely limited by our own imagination only!

Publications:

1. Paper presented at PowerGen Africa Conference July 2017 and published in the conference proceedings titled "Introducing a novel thermodynamic cycle (patent pending), for the economic power generation from recovered heat pumped from the huge global thermal energy reservoir called earth" by Johan Enslin, Heat Recovery Micro System CC. This paper is also accessible from my website http://www.heatrecovery.co.za/.cm4all/iproc.php/PowerGen-Africa 2017 Proceedings Speaker0_Session19149_1.pdf

2. A Paper titled "The Simplified REHOS Cycle.pdf" was written by Johan Enslin in August 2017 and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/The Simplified REHOS Cycle.pdf

3. A Paper titled "Clarifying Process Parameters for the REHOS Cycle Concept_rev3.pdf" was written by Johan Enslin in October 2017 and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/Clarifying Process Parameters for the REHOS Cycle Concept_rev3.pdf

4. The Paper titled "The Binary NH3-H2O Bubble Reactor_rev1.pdf" was written by Johan Enslin in December 2017, and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/The Binary NH3-H2O Bubble Reactor_rev1.pdf

5. The Paper titled "The Competitive Advantages of REHOS Technology_rev1.pdf" was compiled by Johan Enslin in early January 2018, and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/Competitive Advantages of REHOS Technology_rev1.pdf

6. Another paper, "Executive Overview of the REHOS Technology_rev1.pdf" was compiled by Johan Enslin in February 2018 and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/Executive Overview of the REHOS Technology_rev1.pdf

7. The follow-up document "Clarification of COP calculations for Absorption Heat Transformer (AHT) Type Heat Pumps.pdf" was written by Johan Enslin (to enhance the Executive Overview paper) in March 2018 and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/Clarification of COP calculations for Absorption Heat Transformer (AHT) Type Heat Pumps.pdf

8. The document titled "Comparison of various Modern Heatpump Technologies for unlocking Commercial Value from Ambient Heat_rev4.pdf" was written by Johan Enslin in April 2018 and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/Comparison of various Modern

Heatpump Technologies for unlocking Commercial Value from Ambient Heat_rev4.pdf

9. The document "Renewable Energy for Baseload Power.pdf" was written by Johan Enslin in April 2017 and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/Renewable Energy for Baseload Power.pdf

10. The document "The Proof-of-Concept Model of the REHOS Ejector Heat Pump_Part 1.pdf" was written by Johan Enslin in April 2017 and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/The Proof-of-Concept Model of the REHOS Ejector Heat Pump_Part 1.pdf

11. Website for Heat Recovery Micro Systems where the above publications are available from: www.heatrecovery.co.za