<u>Title:</u>
Renewable Energy for Baseload Power

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Global drive to mitigate Global Warming

All nations forming part of the United Nations accepted the Paris Agreement on mitigating climate change, and was officially entered into force on 4 November 2016. The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change.

This give official status to the drive to reduce CO2 emissions and prioritize renewables and other non-carbon power generation globally. This has been coming for some time, however, and utilities have been forced during the last 3 - 5 years already to drastically reduce CO2 emissions, closing coal fired power stations as they become uneconomical due to CO2 penalties and cost of CO2 removal and storage, and embracing renewables (which are incentivized and subsidized) by governments. This create a very large demand for alternative (greener) power generation, like nuclear or renewables.

Developing countries, like many countries in Africa, however, have a huge demand for power generation, but are now also evaluating nuclear and renewables to comply to the UN rules. Cost of power generation is a problem to most governments, however, so the move to reduce CO2 cannot happen overnight. It is rather a slow migration, dictated by financial constrains.

Real Generation Cost Comparison

To be able to compare the real cost of different power generation technologies, it is required to also look at the capacity factor, as well as the useful life of the generation equipment. Looking at nuclear, we see the typical "Overnight" cost = $5776 / kW (inflation adjusted to April 2017 values) installed, but it could run for 60 years, and is capable of delivering power with a capacity factor of as high as 92%. This would produce electricity with a levelized cost of electricity (LCOE) = R1-34 / kWh (assuming ROE of $ = R13-00).

Solar PV as tendered in the Bid window 4 of the REIPPP program have a calculated LCOE = R0-89 / kWh (inflation adjusted to April 2017), but this cannot be compared to nuclear, as the capacity factor (CF) is only a maximum of 25%, as it can only produce power while the sun is shining. To be able to compare this with nuclear, you have to oversize the PV installation and add storage. Storage cost currently is about $300 / kWh, but some manufacturers already claim products as low as $74 / kWh.

Using the CF = 25% and $74 / kWh for 18 hours storage as mentioned, for a utility (100 MW) sized PV installation the "Overnight" cost of $2675-20 / kW calculating to a perceived LCOE = R0-89 / kWh, that need to be oversized to deliver 92% CF => real "Overnight" cost = $9844-74 / kW and the storage cost amount to $1332-00 / kW, added to give $11176-74 / kW and the calculated LCOE = R3-72 / kWh for CF = 92%.

Similarly, for a commercial PV installation (100 kW), the "Overnight" cost of $4358-40 /kW giving a perceived LCOE = R1-45 / kWh adjust to $16038-91 and with the storage of $1332-00 / kW give the real "Overnight" cost = $17370-91 / kW giving the calculated LCOE = R5-78 / kWh for CF = 92%.

Should the national grid be fairly strong (not more than 20% renewables tied to the grid) then the grid may be used as a huge battery, in which case the perceived LCOE values mentioned above are real, and no oversizing with storage are required. Also, should power only be required when the sun shine, the PV installations are about grid parity!

From the calculations above it is clear that the utility sized PV installation produce power at 2,78 times the nuclear baseload value, and the commercial sized PV installation produce power at 4,31 times the nuclear baseload value. From a financial point of view, we are clearly interested in baseload generators only.

Should we add Solar CSP (with storage) the "Overnight" cost run into $7718-00 / kW giving a calculated LCOE = R3-17 / kWh, which is only 2,37 times the nuclear baseload value.

Table 1

Technology	**Overnight Cost $ / kW**	**Storage Cost @ $74 / kWh**	**Capacity Factor (CF)**	**LCOE in (R / kWh)**
Commercial PV	4358-40	0	25%	1-45
Commercial PV	16038-91	1332-00	92%	5-78
Utility PV	2675-20	0	25%	0-89
Utility PV	9844-74	1332-00	92%	3-72
Solar CSP + Storage	7718-00		92%	3-17
Nuclear	5776-00		92%	1-34
Diesel Generation			92%	3-50

If we consider the real LCOE calculated for the two coal-fired power stations currently under construction, Medupi @ R1-08 / kWh and Kusile @ R1-19 / kWh, recognizing that about 50% of the coal-fired power stations used in the South African National Grid have been fully depreciated, we can understand why the average grid parity LCOE = R0-82 / kWh. That highlight the problem that any of the mentioned technologies added to the grid would increase the already high consumer tariff. This is the dilemma that most utilities globally is faced with, and therefore electricity prices rise everywhere as countries are trying to phase out the traditional fossil fueled power generation technology and replace it with nuclear (baseload) and renewables to mitigate global warming.

Thermodynamic efficiency and Waste Heat Generation

Mankind is very good at producing waste heat, especially heat at temperatures lower than 80°C, which are, currently, uneconomical to convert to power. We spend an ever increasing amount of money to mine fossil fuels like coal, oil and gas and then we use combustion processes to convert some of the energy in the fuel into useful entities like electricity and transport power (just to name a few) with efficiencies around 35%. Power generation thermodynamic cycles may deliver electricity at 40 - 46% efficiency, but then you have to deduct the power station own power use for running pumps, fans and other process components. Also, transmission losses from where the power is generated to where it is used may be quite substantial, in the order of 10%, so the national grid electricity reaching the market only represent 30% - 35% (global average of 33%) of the energy in the fuel. The balance is wasted in warming the environment. Even gas fired combined cycles operate with overall efficiencies of 40% - 50% (global average of 44%).

The transport sector is even worse, as the average turbocharged diesel engine operate at only 32% efficiency, while other internal combustion power units for vehicles only reach 25% efficiency, while the balance of heat is wasted. Jet aircraft convert the jet fuel to power with efficiency of around 10% during take-off, but as the speed picks up to cruising speed, the efficiency increase to about 40%.

Total global energy consumption this year come to 176 Billion MWh / annum, increasing at a rate of 1,78% per annum. Of this, we use about 24 Billion MWh / annum (13,8%) for generating electricity, with this figure currently increasing by 2,43% per annum. Some 40 Billion MWh / annum of this total energy use goes to the transport sector, currently growing at 6,13% per annum!

It is interesting to note that the total global energy we consume generate CO2, including the more than 50% waste heat we produce! Should we be able to use even a small portion of this waste heat to generate power, it would not require any additional fuel to be used (and not generate additional CO2), and it would also replace the requirement of the existing 33% efficient power generation! The impact for every kWh of electricity produced from waste heat would therefore save CO2 doubly! The fact that the waste heat source is in very close proximity to electrical connections to the electricity grid (cooling water @ about 40°C from the power station condensers) in quantities greater than the actual current power station electricity output, would make waste heat recovery from existing coal fired and even nuclear generation facilities very cost effective.

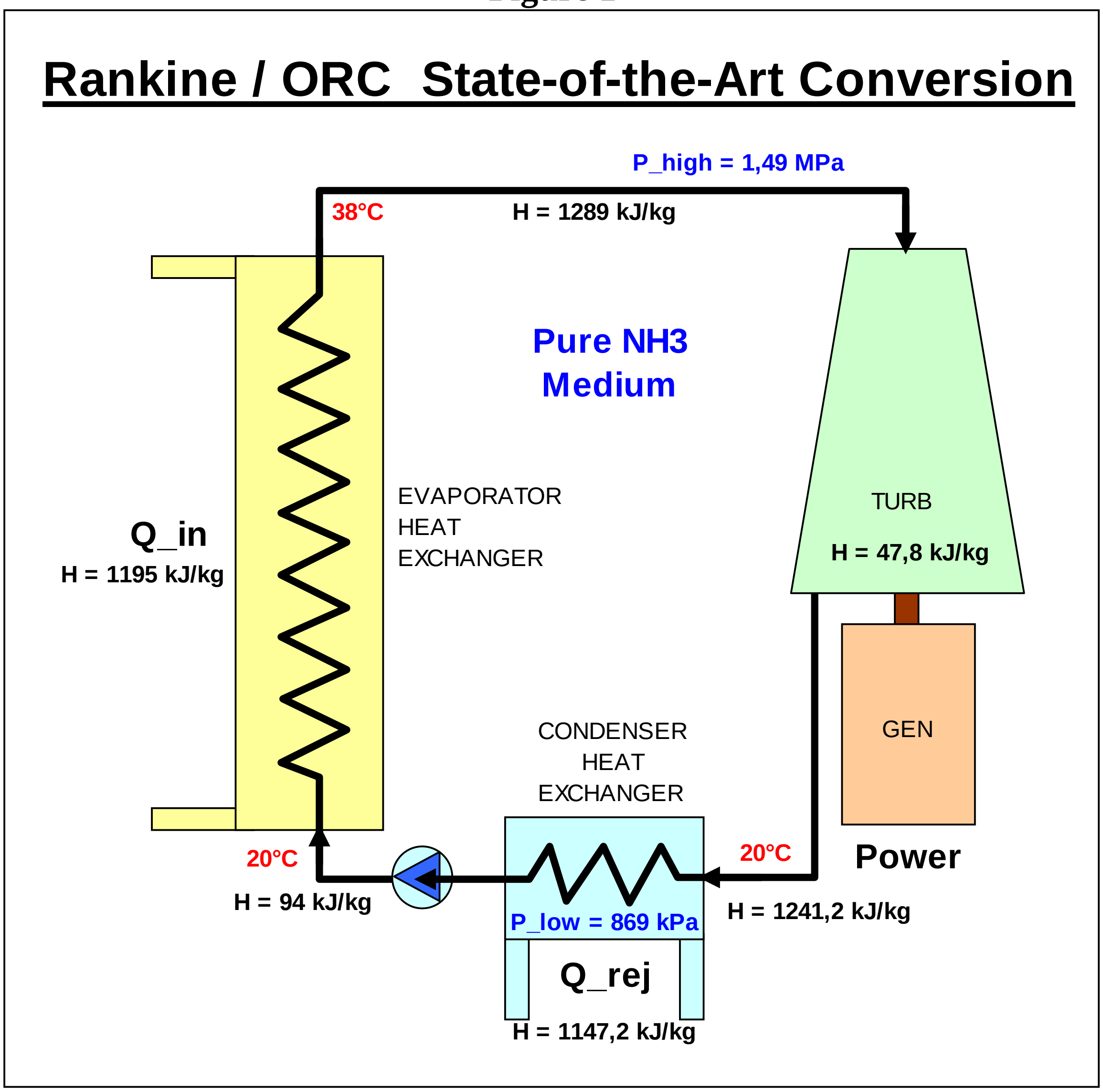
For new power requirements we should keep in mind that the earth continuously receive energy from the sun and after deducting the ~ 30% that is reflected back into space the heat absorbed by earth calculates to more than 6000 times the global energy used by man. Solar thermal energy is therefore readily available everywhere.....

Current Waste Heat Recovery Thermodynamic Cycles

Heat recovery of lower temperature heat sources, typically below 200°C, like geothermal and solar thermal have seen the introduction of organic refrigerants as operating medium, making the Organic Rankine Cycle (ORC) as well as the Kalina Cycle the current state-of-the-art. The higher pressure and density of the organic media at such low differential temperatures deliver much more power at higher efficiencies than what is possible using water/steam at these low temperatures. Currently waste heat at temperatures lower than about 80°C are not considered as economically viable to convert to power on large scale, but it is done on small scale in very specific circumstances.

Figure 1, below, sketch an example ORC to demonstrate the main problem all current state-of-the-art cycles have to content with: In this example, liquid NH3 condensed at 20°C from a condenser is pumped to a pressure of 1,49 MPa (abs) and sent to the boiler heat exchanger, where the liquid is heated to the saturation temperature of 38°C and then evaporated. This HP NH3 vapor is then expanded isentropically in a turbine (or other suitable expander) to generate power. The turbine exhaust is then routed to a condenser, where the vapor is turned back to liquid by rejecting the latent heat in the NH3 vapor to the cooling water in the condenser. The condenser temperature must be as low as possible to ensure a reasonable heat to power conversion efficiency for the thermodynamic cycle, but it depends on the temperature of available cooling water. Obviously, the condenser pressure would be the saturation pressure of the NH3 at the condensing temperature, in our example of Figure 1 we have assumed cooling water of 5°C - 15°C is circulating for keeping the condensing temperature 20°C and the pressure 869 kPa (abs).

Figure 1



Actual ammonia enthalpy values have been filled in on the sketch in Figure 1 above, to demonstrate the limiting conversion efficiency of this thermodynamic cycle. We assumed the low turbine isentropic efficiency of 70% to be realistic. (well designed turbines may have much higher efficiencies in the 80% - 90% range).

The second law of thermodynamics state:

Conversion efficiency (η_cycle) = (Q_in - Q_rej) / Q_in = Power / Q_in

η_cycle = 47,8 / 1195 = 4%

It may also be shown that the ideal (carnot) efficiency may be written as:

Carnot efficiency (η_carnot) = (T_in - T_rej) / T_in = 5,79%

demonstrating that the cycle efficiency of 4% is in fact 69% of carnot, due to the low isentropic power conversion efficiency of 70% assumed for the turbine. Even so, this 4% conversion efficiency make a very waste-full installation, as 96% of the heat flowing through the heat exchangers, are discarded as waste. Also, the hot water providing the heat in the inlet heat exchanger need to have a very large mass flow, as the exchanger can only cool it to the pinch temperature (around 38°C) at which the NH_3 evaporate. This make the total installation very expensive per kilowatt electricity produced!

Looking at a Kalina cycle, the benefit of no boiler pinch may deliver a lot more power density, as heat would be absorbed in the input heat exchanger all the way from the initial inlet 48°C to only a few degrees above the cold condenser inlet temperature. The hot water mass flow entering the boiler heat exchanger would be much smaller than for the normal ORC as it is cooled with a much wider differential temperature, so for heat recovery, smaller (cheaper) exchangers are required. The rest of the Kalina cycle is the same as the drawn ORC, with similar conversion efficiency of around 4%, and it would also reject 96% of the supply heat in the condenser.

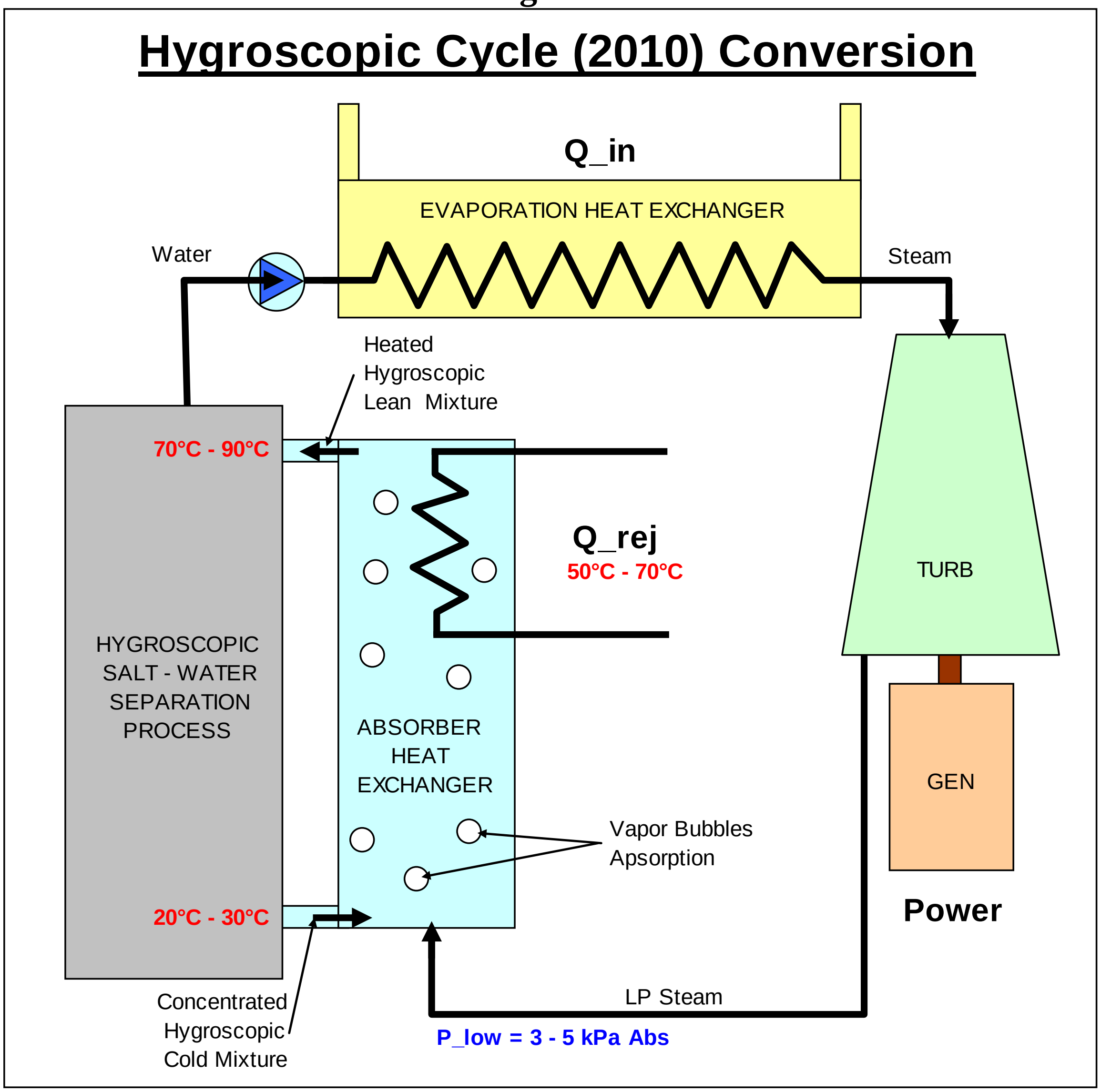
Absorption Refrigeration principles used in Power Generation

Lets have a look at a very interesting recent development to illustrate a very important fact. Figure 2 is a sketch of the Hygroscopic Cycle, patented by F.J.R. Serrano of Spain and published in 2010. A test plant was constructed as recently as April 2015 in Spain to demonstrate the viability of the concept.

This technology is not really for low temperature heat recovery, using the traditional steam turbines, but rather for using as standard utility power generation thermodynamic cycle used in very hot, dry climates where dry cooling is a non-negotiable fact.

The cycle uses water/steam as operating medium, but instead of the standard condenser, it uses an absorber containing hygroscopic material to absorb the LP steam from the turbine rather than condensing it. This have the result we have first seen in absorption refrigeration (and absorption heat transformers or AHT's) developed over the past 20 - 30 years, namely low pressure vapor heating the absorber with the latent heat as well as the heat of solution, without really increasing the absorber pressure. The absorber pressure reflect the low vapor pressure of the hygroscopic mixture, which is much lower than a conventional condenser pressure at the same temperature! A highly concentrated mixture of hygroscopic salts entering the absorber at a low temperature (say 20°C - 30°C) is heated at nearly constant pressure (of some 3 - 5kPa abs) by the LP vapor entering the absorber, to some 70°C - 90°C before exiting the absorber as a heated, lean mixture. This lean mixture is routed through the boiler, boiling off most of the water, to again concentrate the hygroscopic mixture to repeat the cycle.

Figure 2



The rest of the thermodynamic cycle is the same as the well known rankine cycle described earlier, and could be the same as most utility power generators. The biggest advantage of this cycle is that the normal condenser (cold) heat rejection is replaced by the heated high temperature (70°C - 90°C) heat rejection from the absorber. The cooling water therefore does not need to be so cold any more, but may be 60°C - 80°C, as long as it is a few degrees colder than the hot absorber temperature, making air cooling or dry cooling very cheap and practical, even in very hot climates, but retaining the typical utility scale power generator efficiencies because the low absolute pressure in the absorber is the same as what the condenser would have been.

The Game Changer for Waste Heat Recovery

Similar to the Hygroscopic Cycle, the REHOS Cycle use an absorber instead of a condenser, and the cycle is a true binary cycle derived from absorption refrigeration principals, having different ammonia concentrations in different places in the cycle. In the example sketched in Figure 3 below, we used NH_3 in aqua (ammonia and water) as the working medium, but obviously other binary combinations may also be used for different operating conditions.

The Regenerative Heat of Solution (REHOS) Cycle however, have two very unique differences from the Hygroscopic Cycle, namely, firstly, the vapor heated absorber temperature is designed high enough to use as boiler/evaporator to produce the high pressure ammonia vapor required to power the turbine. This is possible with a careful mass- and heat flow balance in the design. This regenerative use of the heating effect of the low pressure turbine exhaust vapor conserve and re-use all the heat that would have been rejected to cooling water in a condenser. The cycle therefore have no official heat rejection, (only heat leakages by non-perfect thermal isolation) resulting in a very high thermodynamic efficiency.

Secondly, the desorption process (grey block in the sketch of Figure 3) is powered by a heat pump internally, to further increase cycle efficiency. In the hot side of the desorber, the rich (~ 20%) NH_3 in aqua liquid mixture give off some nearly-pure NH_3 vapor, condensed in the cold end of the desorber by the heat pump extracting latent heat from the cold end to add to the desorption hot section, while the lean liquid mixture (~ 5%) NH_3 in aqua return to the absorber. These two revolutionary aspects of the REHOS thermodynamic cycle make the efficiency calculation look quite different, but starting again with the second law of thermodynamics:

Again, ignoring pumping power and radiation heat dissipation from hot components,

$$\eta_{cycle} = (Q_{in} - Q_{rej} - Q_{desorb}) / Q_{in} \qquad = Power / Q_{in}$$

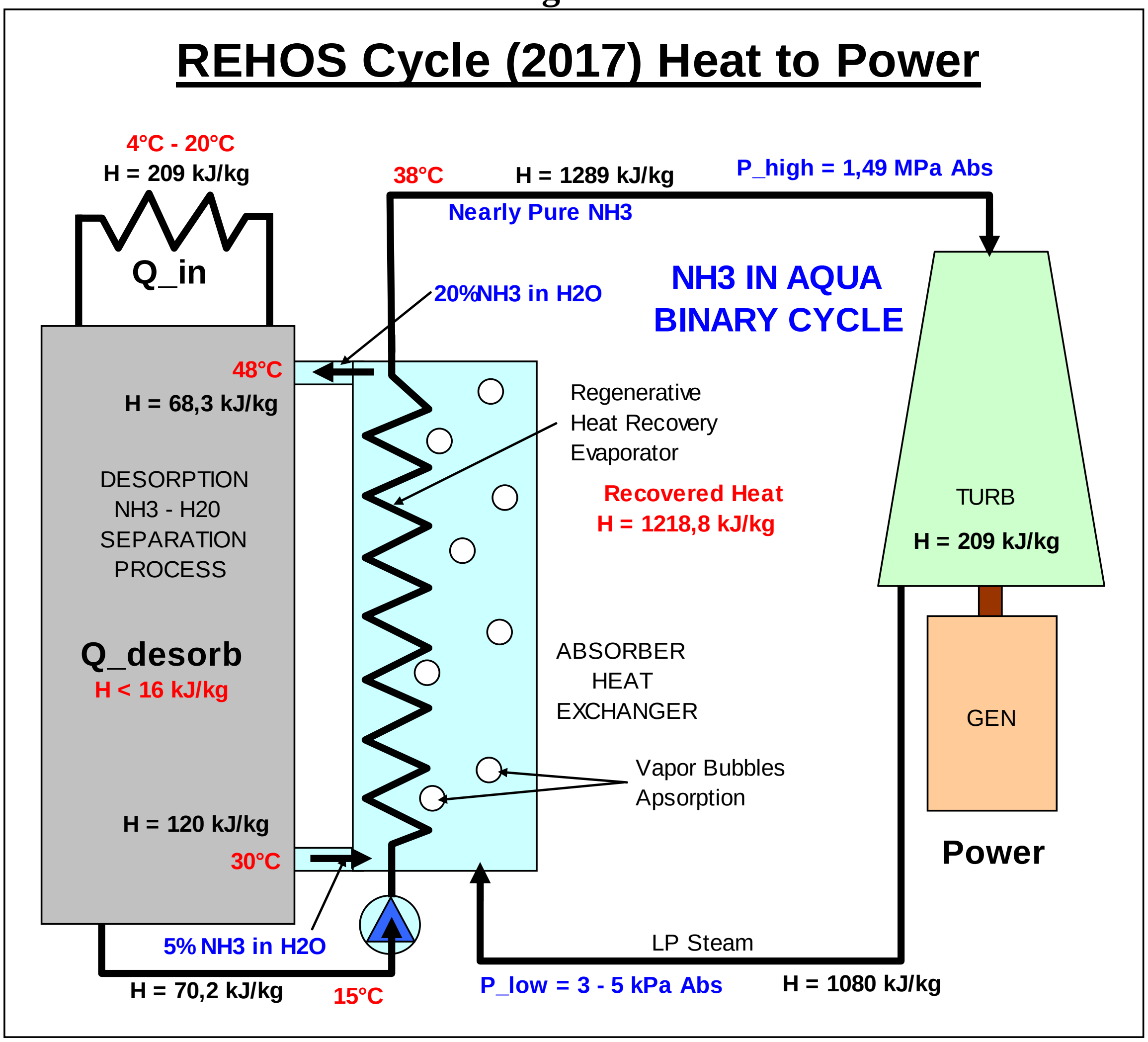
$$\text{with } Q_{rej} = 0 \qquad \Rightarrow \eta_{cycle} = (Power - Q_{desorb}) / Q_{in}$$

$$\eta_{cycle} = (209 - 16) / 209 \qquad = 92\%$$

Note that the desorption process use very little energy, as confirmed by numerous heat and mass balance calculations conducted, using the referenced information. In reality the radiation heat leakage loss and pumping power required by the cycle would decrease the efficiency still further, but can be expected to be **η_cycle = 80% - 90%.**

The REHOS cycle actually consist of two parallel thermodynamic cycles, the heat extract part being an absorption refrigeration cycle, while the power generation part tied into it contain the turbine exhaust waste heat recovery into a shared absorber. The external input heat is extracted from a heat exchanger flashing liquefied NH3 to either desorber pressure (at temperatures of 0°C to 20°C with power density of ~ 160 kW / kg NH3) or absorber pressure, in which case heat may be absorbed from as low as -28°C (giving power density of ~ 140 kW / kg NH3), as the absorber pressure is around 1 Bar (abs). This make the cycle extremely versatile, as it may even absorb ambient heat from the environment to generate power from.

Figure 3



Costing aspects of the typical REHOS cycles.

As the REHOS cycle consist of 3 heat exchangers and 2 pumps coupled with a turbine or other expander, eg. Lysholm Screw, Scroll or other dense fluid positive displacement expander, it is not difficult to realize the capital investment required for the REHOS installation (even for a small 10 kWe unit) would easily match the cost of utility scale Solar PV installations per installed kWe, but obviously the REHOS generate power from waste heat, available anywhere and any time, so it produce BASELOAD power able to produce power with a capacity factor (CF) of 92%, matching the nuclear baseload power generator for the same capital cost delivering electricity with LCOE < R0-82 / kWh.

The high thermodynamic conversion efficiency (80% - 90%) and low capital investment requirements would guarantee generation cost below the current average grid parity, making it the cheapest baseload power generator technology ever, able to operate 60% cheaper than nuclear. It is also able to be made modular, and scalable from a few kWe to several MWe so implementation is very practical.

Extracting heat from the cooling water of existing power stations have the advantage of increasing a power station generation capacity by 100% (as most power stations reject more heat in the condenser than the actual power produced) without interrupting the current station operation. REHOS modules could be added as and when required to gradually allow the station to operate on lower main steam pressures to extend it's life resulting from less stresses in the boiler pressure parts. Also, cooling the CW have a lower condenser pressure as a result, again increasing the station capacity. Reclaiming the waste heat from the cooling water would leave less heat in the cooling water to be dissipated by evaporation (wet cooling generators) and therefore the power station would use less water! As the electricity infrastructure and national grid connections are already available on the existing power station, it may easily be shared with new REHOS modules added. Each addition of modular REHOS Generator cycle would reduce the power station CO_2 produced as well as water used and allow the old station to be de-rated somewhat to conserve operation life.

Adding a REHOS cycle as bottoming cycle to existing fossil (and nuclear) power generators would change the power station efficiency to ~ 60% from the original 33%, with the station CO_2 produced is cut in half! This would be the case also for solar thermal power generation, as they also use the rankine power block and reject about 60% of the solar input heat collected from the sun in cooling towers.

Newly built power generation may want to extract environmental heat (supplied by the sun) in high density water media (to keep heat exchangers small and cheap) like pools, rivers, dams, lakes and the sea, where REHOS cycle power may be utilized. Obviously, it may also be used to power marine transport and even replace internal combustion and diesel power used for land transport, as a fairly small heat exchanger (about twice the normal currently used vehicle radiators) would be required to extract ambient heat from the air to power the vehicle.

REHOS cycle add-on to water pumps may be powered by extracting the waste heat in the water being pumped, making water pumping essentially free! We know that the energy requirement for water desalination by reverse osmosis is almost entirely resulting from pumping energy requirements. The uses of this REHOS cycle is only limited by our limited imagination, and everywhere it is used, it replace the culprit CO_2-emitters and power becomes very cheap and "green", without any emissions released.

Large scale roll-out of the REHOS cycles are very likely driven by economic reasons and would be helping governments globally achieve the ambitious goals set for CO_2 reductions to conform to the Paris Agreement committed to with the COP21 meeting of the United Nations! It would also stimulate economies massively and the decreasing cost of electricity globally would stimulate job creation for economic expansion in ways we can barely imagine. What better way of fighting global warming can you imagine than having human greed drive fossil combustion replacement? This is the revolution!

The Prototype Project for Cooling Tower Heat Recovery:

Although numerous different temperature and pressure experimental REHOS cycles were analyzed with heat balance, mass- and %NH_3 balance calculations proving the performance have been conducted, we embarked on the design and construction of a proof of concept (PoC) Model and plan to complete this by mid-year. I have also booked a time-slot in the Power-Gen Africa Conference on 18-21 July 2017 where I will be launching the REHOS technology officially.

I'm in the process of setting up a Commercialization JV to kick off the end of July with all the necessary parties to provide Financing, Construction as well as Academic expertise to initially construct a small (maybe ~ 10 kWe) pilot plant, followed by a larger (a few MW) commercial prototype for finalizing the IP protection and licensing to consultants, manufacturers and large users globally.

Should your company have an interest to participate in the commercialization of this revolutionary novel technology, do not hesitate to contact myself, preferably by e-mail.

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