On Storm Energy

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"You're unlikely to discover something new without a lot of practice on old stuff".
Richard Feynman

Abstract

The atmosphere is an engine wherein heat is converted to mechanical energy. The atmosphere is heated from the bottom by solar radiation and cooled from above by infrared radiation to space. There is a potential for producing work because the heat is received at higher temperature than at which it is given up. *The maximum quantity of mechanical energy that can be produced when an air mass is moved is equal to the reduction in its enthalpy minus the increase in its potential energy.* This ideal work is the same for all reversible adiabatic processes. Ideal work of humid air is a function of its initial conditions (pressure, temperature, and mixing ratio), of its final pressure and of its change in elevation.

To the flow of heat is due all motion including every form of atmospheric motion. Mechanical energy is more valuable than thermal energy. In ideal processes, mechanical energy can be transformed from one form to another reversibly without loss. Mechanical energy can be transferred from one place to another. Mechanical energy can degrade to heat; the fraction of heat that can be converted back to mechanical energy is limited by the second law of thermodynamics, by Carnot efficiency.

The determination of efficiency is the fundamental problem of atmospheric energetics. Estimates of atmospheric efficiency range from over 12 %, based on the Carnot efficiency for the average temperatures at which heat is received (290 K) and given up (255 K) to less than 1 % based on estimates of dissipation and on models. Estimates of average per unit area atmospheric power production range from 1 to 10 W/m^2. Estimates of total atmospheric power production potential range from 600 to over 6000 TW. Human primary and electrical power productions are 30 and 3 TW, respectively 0.5 and 0.05 % of the upper 6000 TW estimate of the atmospheric potential.

The wide range of atmospheric efficiency is due the fact that actual efficiency can be much lower than ideal efficiency. The efficiency of early steam engines was much lower than their Carnot efficiency because, without appropriate mechanisms, work degrades to heat. The efficiency of an idling engine is zero.

This article uses steady-state open thermodynamic processes and close thermodynamic cycles to show that the atmosphere has the potential to produce the higher 12 % efficiency estimate. The total energy equation is widely used in engineering is more effective than the usual atmospheric science approaches. The *total energy equation approach* is used to explain the energy of tornadoes and of hurricanes. The *approach* is illustrated with the Jordan mean hurricane season Caribbean sounding.

The divisor for efficiency is the upward convective heat flux at the bottom of the atmosphere of ≈50,000 TW (≈100 W/m^2) and not the incoming solar radiation of 178,000 TW; 6000 TW is 12 % of 50,000 TW and 3.4 % of 178,000 TW. Solar radiation reflected to space and infrared radiation to space from the lower atmosphere do not contribute to work production because the heat is not carried by convection.

Atmospheric work production could be concentrated in a small area to produce clean electrical energy. An atmospheric vortex engine (AVE) would have an area of less one square kilometer and produce 2 GWe, as much electrical energy as a large thermal power plant. A solar power plant requires a collector area of 200 km^2 to produce 2 GWe. AVE's could convert 25 % of supplied low temperature heat to work. A large tornado can produce ≈10 GW of mechanical energy. A large hurricane can produce ≈10 TW of mechanical energy, three times more than human produced electrical energy. Work production can be increased by increasing the enthalpy of the raised air with low temperature heat sources. Increasing enthalpy of the air by spraying it with warm water downstream of the expander could permit using heat sources with temperatures as low as 25°C.

The focus of this article is on thermodynamics of the atmospheric process. The conclusions are applicable to the atmosphere in its natural state and to processes for harnessing its energy such as the AVE. This article does not describe AVE implementation options which have been presented elsewhere, see Michaud (1975, 1999). This article is based on atmospheric science, on engineering principles and on process control experience. The references are not limited to the peer reviewed literature.

1. Introduction

The atmosphere can be viewed as an array of air reservoirs. Moving air from one reservoir to another can produce work. The source reservoir can be the lower atmosphere. The receiving reservoir, the environment to which the air is moved, can be the upper troposphere. The work is *free* in the sense that there is no need to provide costly high temperature heat. The work is produced from the pre-existing natural heat content of the raised air.

Fig. 1 shows a thermodynamics system applicable to any open steady-state, continuous flow, single input and single output process. Conservation of energy requires that external energy inputs equal external energy output. The first law of thermodynamics, for an open, steady-state, continuous flow system is:

$$W = -\Delta H - \Delta gz - \frac{\Delta v^2}{2} + Q \qquad (1)$$

where: *W* is the work leaving the system, *H* is enthalpy, *g* is acceleration of gravity, z is height, *v* is velocity and *Q* is heat received. All terms are in Joules per kilogram. See Smith and Van Ness "Introduction to Chemical Engineering Thermodynamics" chapter 2, Eq. 2.32.

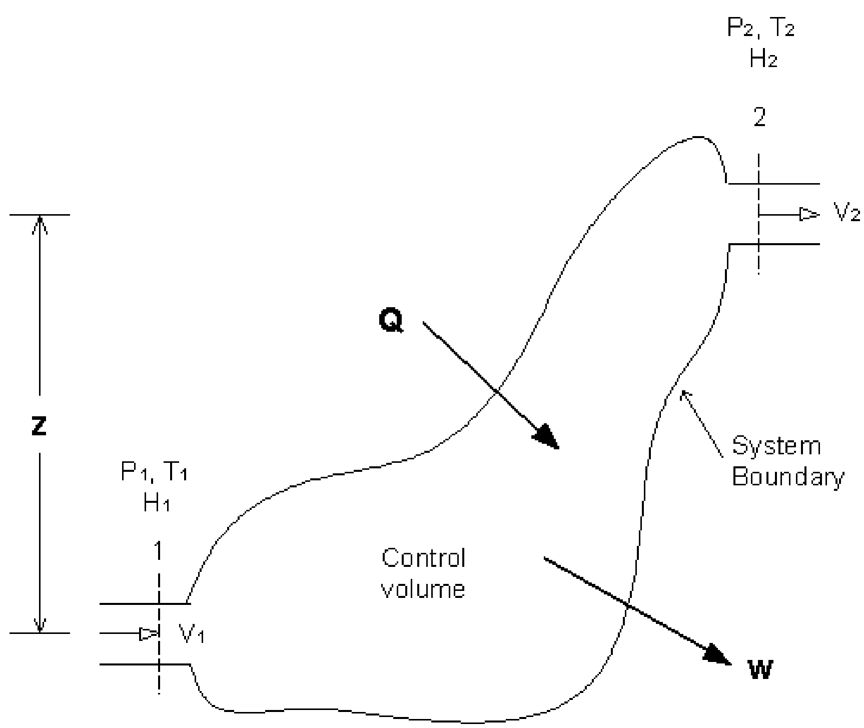


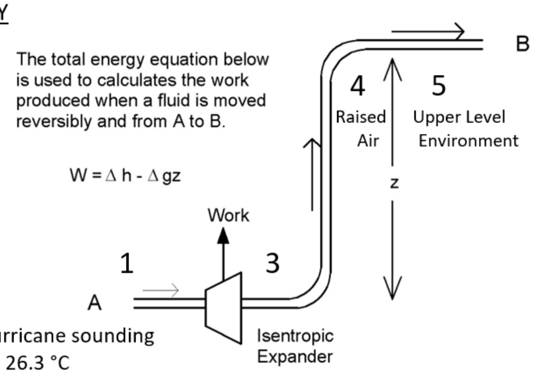
Figure.1 Energy balance for open continuous steady-state thermodynamic system,with one inlet and one exit.
Based on Smith and Van Ness Figure 2.6

The *ideal work* (W_b) for a reversible process with no heat transfer, with negligible velocities and with no degradation of work to heat by friction is:

$$E_z = W_b = -\Delta H - g\,\Delta z = -\Delta\mu \qquad (2)$$

Q and Δv are zero for adiabatic ideal processes. μ is the moist static energy of the flowing air. This ideal work will be called *ezergy* (E_z) to highlight the change in elevation (Δz). *Ezergy is equal to the decrease in enthalpy minus increase in potential energy of the raised air*, more concisely to decrease in the air's moist static energy. *Ezergy* is the maximum quantity of work that can be made available when an air mass is moved reversibly without heat transfer. W_b stands for work of buoyancy and is just another symbol for E_z; the corresponding W_p stands for potential energy of condensed water and is not shown explicitly in (2) because it is included in the Δgz term.

EXERGY vs EZERGY



Basis:
Jordan Caribbean hurricane sounding
P_1 = 101.51 kPa, T_1 = 26.3 °C
U_1 = 84.03 %, M_1 =18.20 g/kg
True adiabatic with ice. s1 = s3 = s4 = 253.0 J/(K.kg). h1 = 72822 J/kg.
s_{15} = 226.1 J/(K.kg), h_{15} = - 76517 J/kg
$W_b = W_{13}$ = Turbine Work. W_p = PE of condensed water. $W_t = W_b + W_p$.

EZERGY / Total Energy Equation Method: $W_b = (h_1 - h_4) - (1 + M_1)\Delta gz$

P_4 (kPa)	P_3 (kPa)	z_4 (m)	Δh (J/kg)	Δgz (J/kg)	W_b (J/kg)	v (m/s)	W_p (J/kg)	W_t (J/kg)	ΔT_4 (K)
20	99.36	12400	125621	123736	1885	60.3	2186	4071	9.8
15	98.99	14182	143731	141516	**2215**	65.4	2525	4740	5.3
12.64	99.05	15292	153855	151692	**2163**	64.6	2710	**4873**	0.0

EXERGY / Gibbs Method: A = $(h_1 - h_5) - T_0 (s_4 - s_5) - (1+ M_1)$ gz

P_4(kPa)	z_4(m)	Δh(J/kg)	$T_0\Delta$s(J/kg)	Δgz(J/kg)	A(J/kg)	W_p(J/kg)	W_t(J/kg)
20	12400	136272	10417	125117	2119	2204	4324
15	14182	149338	5535	141516	**2286**	2527	4813
12.64	15292	153862	6	149002	**2163**	2710	**4873**

@ 15 kpa: A – W_b = 2286 – 2215 = 71 J/kg is the extra work produced by cooling the raised air from T_4 to T_0 with a reversible Carnot engine.
@ 12.64 kPa: at temperature equilibrium, A - W_b = 2163 - 2163 = 0

Fig. 2 Ideal work for surface air raised to a range of levels.

Figure 2 shows an example of an ideal open reversible adiabatic process moving air from the bottom to the top of the troposphere. Work degradation through friction and kinetic energy change are negligible because velocity is low. There is no heat transfer because the conduit is perfectly insulated. Conservation of energy requires an expander or turbine with a shaft to get the mechanical energy out of the system.

The three cases show the effect of final pressure on ideal work. An adiabatic reversible process is a constant entropy (S) process, $S = C$. From known initial air conditions and final pressure, the final temperature for a constant entropy process can be calculated with a solver. Ezergy can then be calculated from the known initial and final enthalpy and the change in elevation.

Ezergy peaks when the air is raised to the level where the pressure is approximately 15 kPa. The troposphere is cooled by radiating heat to space by approximately 1.5°C/d; there is little radiative cooling above the top of the troposphere which is near the 15 kPa level.
The 15 kPa elevation is ≈14.2 km in the tropics and ≈13.2 km in high latitudes. Figure 2 is based on the Jordan mean Caribbean hurricane-season sounding. Ideal work for surface air peaks at ≈2215 J/kg for surface air raised to the 15 kPa (14182 m) level.

Willard Gibbs showed that ideal work, which he called free energy, for a fluid brought reversibly to equilibrium with different environment with reversible heat transfer is:

$$A = E_x = -\Delta H - T_o \, \Delta s - g\Delta z \qquad (3)$$

See Smith and Van Ness (eq. 5.24 and 5.27). Gibbs free energy is now called *exergy*. The usual symbol for *exergy* is A. The symbol E_x will be used for exergy for consistency with E_z ezergy and other types of free energy. T_o is the temperature of the final environment; ΔH is the difference between the enthalpy of the raised air in its initial state and of the enthalpy of the environment at the final state. In Figure 2, for surface air raised to the 15 kPa level, the *exergy* is 2286 J/kg. The *exergy* is slightly larger than the ezergy of 2215 J/kg because a Carnot engine producing a small amount of work could be used to bring the temperature of the raised air to the temperature of the final environment. The 12.64 kPa case of Figure 2 shows that ideal work and exergy are identical for air raised to the level of temperature equilibrium because there is no need to transfer heat via a Carnot engine to reach temperature equilibrium.

Exergy is the maximum work that can be produced when a fluid is brought reversibly to full equilibrium with an environment. The name *exergy* was coined by Rant, see Marquet (2014). There is no currently defined name for the ideal work of eq. (2) "where a fluid is brought reversibly to a different pressure, without heat transfer and without bringing the fluid to temperature equilibrium with the final environment." Eq. (2) is widely used in engineering. There is a need for a name for this type of free energy; it is proposed that it be called *ezergy* (E_z) to indicate that there is a change in elevation (z). The potential energy of condensed water (W_p) is not included in exergy or in ezergy because lifting the waters is essential to the production of the work.

Ezergy (E_z) is a good approximation of exergy (E_x) when the final temperature of the raised air is close to that of the final environment. For deep convection, the ezergy of air raised to the 15 kPa level is a fair approximation of the peak ezergy. Warm humid surface air has exergy and ezergy.

For a process without change in elevation, the $g\Delta z$ term in (3) is zero. Ezergy when there is no change in elevation will be called *emergy* (E_m), where the "*m*" indicates same (même) elevation. In figure 2, the ezergy of the overall process E_z is equal to the turbine emergy, (E_m) because the turbine is the only flow restriction. *The emergy of a gas turbine is simply its ideal work.* The appendix summarises proposed names for the different types of free energy.

For given inlet and outlet conditions, ezergy is identical for all reversible adiabatic processes. There are many possible lifting processes; the process could be a batch discontinuous process rather than a continuous one; the conduit could have a snaky or spiral shape. The conduit could be cone shape to make exit velocity negligible. The conduit need not be vertical and can have a gradual slope because horizontal spacing is not a factor in an ideal process with no friction loss.

In an ideal process, there must be an isentropic expander or turbine to get the work out of the system. The turbine can be at any point in the conduit. The ezergy is produced by the expanding/rising air and is captured by the turbine where the flow is restricted wherefrom it leaves the system as shaft work. There is no need for the diagram of figure 2. All that is required to calculate ezergy is to know the initial and final conditions. Ezergy can be calculated from pure thermodynamics; there is no need for a physical model. *Ezergy is simply the maximum quantity of mechanical that can be produced when air is moved from one location to another without heat transfer.*

Actual work, W_a , for an irreversible process is smaller than ezergy, E_z , because ezergy easily degrades to heat. For the same initial and final conditions, the enthalpy reduction, (ΔH) in eq. (2), is smaller for an irreversible than for a reversible process. For a fully irreversible process $W = 0$ and $\Delta H = \Delta gz$; all the work degrades to enthalpy. The process of Figure 2 can be made irreversible by replacing the turbine with one or more restrictions. Actual work (W_a) is smaller than ezergy (E_z) in irreversible processes or in processes with significant exit kinetic energy.

Ezergy is akin to Convective Available Potential Energy (CAPE) which is widely used in atmospheric science, and which is the kinetic energy acquired by a buoyant air mass rising without heat exchange, friction or mixing. CAPE is based on Newton's laws; exergy is based on conservation of energy. The acceleration depends on the difference in density between the rising air and the surrounding air which changes with elevation. CAPE implies that the air accelerates as it rises, but the mechanical energy can take other forms.

There are many flavors of CAPE: CAPE-500 based on average properties of bottom 500 m of the atmosphere, surface CAPE (SCAPE), 2-m CAPE and 10-m CAPE. CAPE-500 is the default and can be much smaller than SCAPE. CAPE calculations can be based on actual or on virtual temperature. There are also various methods of calculating the expansion temperatures used

to calculate CAPE. CAPE calculations start at the level of neutral buoyancy (LNB). Ezergy calculations start at the initial air position and include convective inhibition (CIN). For expansion without separation of condensed water, ezergy is the algebraic sum of CAPE and CIN.
Ezergy = CAPE + CIN because both relate to conservation of energy.

Exergy and CAPE both assume that there is no dilution of the rising air by surrounding ambient air and no friction. Deep convection (>10 km) is rare; shallow convection (<3 km) is ubiquitous. Deep convection requires that evaporative cooling be reduced by centrifugal force or by high humidity aloft. Shallow updrafts increase humidity aloft making the environment more favorable for deep convection. Evaporative cooling associated with entrainment reduces buoyancy, Michaud (1998).

Exergy is produced when warm/humid air is raised. In steady-state conduit flow, the shaft work is produced wherever in the conduit the isentropic turbine is located. In a conduit, work is transferred from where it is produced to where the flow is restricted. Figure 2 shows that the work can be transferred to a horizontal turbine located at grade. The horizontal conduit at the bottom of Figure 2 could be several thousand kilometers long because there is no friction loss in an ideal process. The turbine could be located at the upstream end of this conduit. The point where the shaft work is produced could be several thousand kilometers away from where the upflow and most of the expansion occur. As a default Ezergy can produce a velocity of $2\sqrt{E_z}$ throughout the length of the conduit. The kinetic energy can become the exit velocity or can be partly extracted with expanders located anywhere in the conduit.

In a continuous process, the exergy of the raised air is determined by the pressure and elevation of the final reservoir. The density of the environment does not matter except for its effect on the final elevation. CAPE calculations must consider the density at every level. Ezergy calculation only need to consider the pressure and elevation of the final position. The effect of convection on final elevation is negligible because the subsidence takes place in remote locations. The passage of a large hurricanes has little effect on the geopotential height of the 15 kPa pressure level in the hurricane formation areas. The effect of changing the level of the final elevation is small compared to that of changing the initial air temperature or humidity.

In continuous processes, work is transferred to wherever the flow is restricted. In Fig. 2 the turbine can be located anywhere in the vertical tube or in the horizontal conduit as shown. Expansion is at constant entropy throughout the conduit including at the turbine. *Ezergy is real work, it can produce shaft work or kinetic energy; it can produce vertical or horizontal velocity.*

Computational fluid dynamics models (CFD) have difficulty arriving at the conclusion that work of convection can be concentrated and captured at one location. Thermodynamics analysis require that there be an expander via which mechanical shaft work leaves the system. Thermodynamics specifies the flow and calculates the maximum work. CFD calculates the flow, which is very difficult since there are many possible paths. Atmospheric efficiency is an oxymoron because there is no shaft through which work can leave the system. Since there is no way for work to leave the system, all the work eventually reverts to heat. Atmospheric energy calculations do not show the expander because there is none in the atmosphere. The expansion cannot be isentropic without a way of getting the work out of the system. Ideal cycle analysis is impossible without an expander.

Mechanical energy can be converted reversibly from one form to another. It can degrade to heat due to viscous friction, mixing or because there is nothing to push against like in an unrestrained piston. Kinetic energy is difficult to calculate because most of the ezergy degrades back to heat without producing significant kinetic energy. Zipser and LeMone (1980) showed that the kinetic energy of strong GATE updraft is typically less than 4% of CAPE. *Ezergy* is more appropriate than *exergy* for atmospheric problems because there is no practical way of producing work from small temperature differences, especially if the Carnot engine must be located at the tropopause.

Enthalpies and entropies values are based on Dufour and Van Mieghem: "Thermodynamique de l'Atmosphère". The zero for enthalpy (*H*) and entropy (*S*) is 0 °C and 100 kPa for air and liquid water at 0 °C. A 20 °C freezing band is used to avoid having a discontinuity at the freezing point. The condensed water starts to freeze at 0 °C and is 50 % liquid at -10 °C. The freezing band has no effect on ezergy when the final air temperatures is less than -20 °C.

References, Michaud (HP48), provides a link to the HP48 calculator atmospheric thermodynamics program AT1 used for ezergy calculations. The program is available at the vortexengine.ca web site and is an invaluable tool. HP48 calculator emulators are available for most computers and smart phones are widely available and free.

In this article, ezergy calculations are based on expansion with freezing and without separation of the condensed water. Molinari's Figure 3 shows that CAPE for true-adiabatic expansion with freezing and no separation is almost identical to CAPE for pseudo-adiabatic expansion without freezing. True-adiabatic expansion can be carried out in a single step; pseudo-adiabatic expansion requires multiple steps. Pseudo-adiabatic expansion is just a succession of true-adiabatic expansions followed by separation. The potential energy of the condensed water (W_p) is smaller in the pseudo-adiabatic case than in the true-adiabatic case.

In this article, the enthalpy (*H*) of moist air is the sum of the enthalpy of one kilogram of pure air plus the enthalpy of its water content in any phase. Energy values are per kilogram of dry air plus its water content in any phase. In Figure 2, 1 kg of dry air contains 1.0182 kg of substance because the mixing ratio is 18.2 g-water/kg-air. The potential energy term must be multiplied $(1 + m) = 1.0182$ where m is the mixing ratio in kg-water/kg-air. The ezergy is 2215 Joules per 1.0182 kg of substance or per kilogram of pure air plus its water content. The ezergy per kilogram of substance is 2215/1.0182 = 2175 J/kg of substance. Both values correspond to a velocity of 66.0 m/s.

The enthalpy of the 85 % relative humidity air at the base of the Jordan sounding is 72,820 J/kg; the enthalpy of dry air at the same pressure is 26,420 J/kg. The contribution of water vapor to enthalpy is 46,400 J/kg. Water vapor contributes 1.8 % of the mass content and 63.7 % of the heat content.

Ezergy equation (2) is applicable to any mass of fluid including all components in any phase. In figure 3, the mass of dry air is 1 kg in all three cases, the mass of water is 16.95 g in case 1 and 18.01 g in case 4. Keeping the air mass constant simplifies calculations. The ezergy equation is valid for rising or descending air. For the Jordan sounding, lowering a kilogram of ambient air from the 15 kPa level adiabatically to the surface has an ezergy of -11100 J/kg; lowering upper troposphere air requires rather than produces energy.

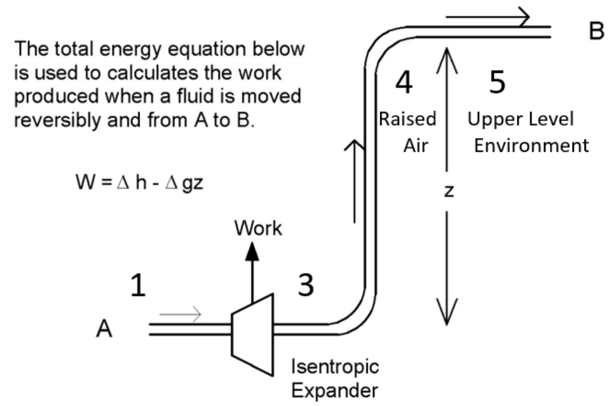
Ezergy is independent of time and velocity. Per unit mass calculations permit comparisons of different cases. Ideal power is specific ezergy multiplied by flow in kilogram per second.
A standard flow of 10000 kg-air/s will be used to provide an appreciation of the power production potential. A small tornado with a 30 m base diameter could have an upward flow of 10000 kg/s (10 t/s). At this standard flow, an ezergy of 2215 J/kg correspond to a power output of ≈22 MW. For a given upward velocity, flow increases with the square of diameter. Power potential is proportional to ezergy and to the square of vortex base diameter. For the same conditions, a vortex with a 300 m diameter vortex could produce 2200 MW of mechanical energy.

Friction losses are much higher for non-continuous cumulus batch flow than for continuous flow. For the same continuous flow friction losses are inversely proportional to the fourth power of conduit diameter for laminar flow and to the fifth power of conduit diameter for turbulent flow. Friction losses for the above standard flow could be 20 MW for batch flow, 2 MW for turbulent flow in a tube or chimney and 0.1 MW for laminar flow in a vortex. Shear is much higher in turbulent flow than in laminar flow. For large diameter vortices, friction losses are a small fraction of ideal power.

2. Effect of surface air temperature and humidity – Tornadoes and dust devils

Fig. 3 and 4 show the effect of surface air temperature and humidity on ezergy. Increasing surface air temperature by 1°C, at constant mixing ratio, increases ezergy by 316 J/kg. Increasing surface air mixing ratio by 1 g/kg, at constant temperature, increases ezergy by 695 J/kg. Increasing surface air temperature by 1°C, at constant relative humidity, increases ezergy by 1044 J/kg. The incremental efficiency (RZ), the ratio of ezergy increment to heat increment ranges from 27.2 to 30.5 %. RZ is slightly higher for sensible heat addition than for latent heat addition because there is no need to raise additional water.

Converting 30 % of heat received at a temperature of 30°C would be a feat for any engine. Conventional thermal engines typically require heat source temperatures of at least 300°C. The reason for the high incremental efficiency is that the air previously received heat through natural processes as will be shown in the close cycle analysis in the next section. The reason for the ability to produce work from small temperature differences is that a small reduction in density is enough to make a fluid rise and to produce upward heat convection.



Basis:
Jordan Caribbean hurricane sounding
P_1 = 101.51 kPa,
P_4 = 15 kPa, Z_4 = 14,182 m
True adiabatic with ice.
$W_b = W_{13}$ = Turbine Work (Ezergy).

Total Energy Equation Method: $W_b = (h_1 - h_4) - (1 + M_1)\Delta gz$

Reversible								Irreversible	
T_1 (K)	U_1(%)	M_1(g/kg)	W_b(J/kg)	$\Delta W_b/\Delta x$	H_1 (J/kg)	ΔH_1 (J/kg)	RZ (%)	W_i(J/kg)	RI(%)
27	75	16.95	1564	Base	70361	Base	Base	2232	Base
28	70.6	16.95	1880	316 J/K	71397	1026	30.5	2679	43.6
27	79.4	17.95	2259	695 J/g	72912	2551	27.2	3183	37.3
28	75	18.01	2608	1044 J/K	74100	3739	27.9	3667	38.4

Carnot Efficiency = $1 - (T_4/T_1) = 1 - (209/301)$ = 30.5 %.

Figure 3. Effect of increasing surface air temperature and humidity on ezergy and on efficiency.

The previous calculations are for a reversible process where the work leaves the system. In a fully irreversible process, dissipated work (*Wi*) is more than the corresponding exergy because the dissipated energy becomes heat which produces additional work. In the second case of Figure 3, the reversible exergy and irreversible dissipated work are 1880 and 2679 J/kg respectively. Dissipation increases work production by 42 %. The pressures at the base of the updraft decreases by 0.9 kPa from 99.38 to 98.48 kPa. The work dissipated (W_i) in an irreversible process will be called *inergy* (E_i) where (*i*) stands for irreversible.

Fig. 4 shows the effect of surface air temperature and humidity on ezergy and on peak ezergy level. Peak ezergy occurs close to the 15 kPa (14.2 km) level in every case. The negative ezergy at low elevation is akin to convective inhibition (CIN). Surface air can be in a metastable state and may have to be raised several kilometers to produce significant positive ezergy. Ezergy is transferred downward to the turbine where the flow is restricted and to overcome resistance to flow wherever it occurs in the conduit, including raising surface air up to the level where it becomes buoyant. Any excess of work of expansion beyond what is required to raise the air is transferred to the turbine which produces work which can leave the system via a shaft.
A temporary heat source or other disturbance could be used to overcome the metastable state and to start the flow. Starting the upward flow is akin to starting a syphon or a thermosyphon.
In figure 2, the maximum ezergy level (15 kPa) is slightly lower than the temperature equilibrium exergy level (12.64 kPa) because there is less work required to raise water.
Decreasing the relative humidity of 27°C surface air from 75 % to 64 % would reduce exergy from 1564 J/kg to zero.

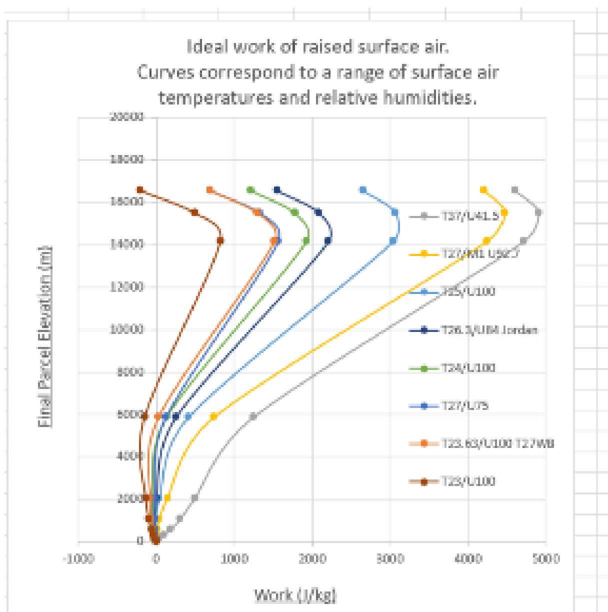


Fig.4 Effect of surface air temperature and humidity on ezergy.
Based on Jordan hurricane-season sounding.

Fig. 5 shows the effect of initial pressure or elevation on ezergy. Ezergy decreases rapidly with increasing source air level. The ezergy of air initially at the 95 kPa level is half of that of surface air. The ezergy of air initially at 90 kPa is close to zero. Ezergy decreases rapidly with initial elevation because mixing ratio decreases with elevation. The relative humidity of maritime tropical air can be 85 % and 60 % at the sea surface and at the 3 km level respectively. The corresponding mixing ratio can be 17 and 6 g-water/kg-air. Mixing ratio and ezergy both decrease rapidly with initial elevation.

Raising high enthalpy surface air is the atmosphere's main work production process. A short stack should help prevent the base of a vortex from drifting away from a vortex engine because of the low heat content and mixing ratio of air at higher elevation. The energy of tornadoes is often attributed to descent from above. Figure 5 shows that such an attribution must be incorrect; lowering upper troposphere air does not produce energy, it requires energy. The cooling of upper troposphere air by rain or by mixing with clouds can produce intense downdrafts but updrafts are required to produce the condensed water.

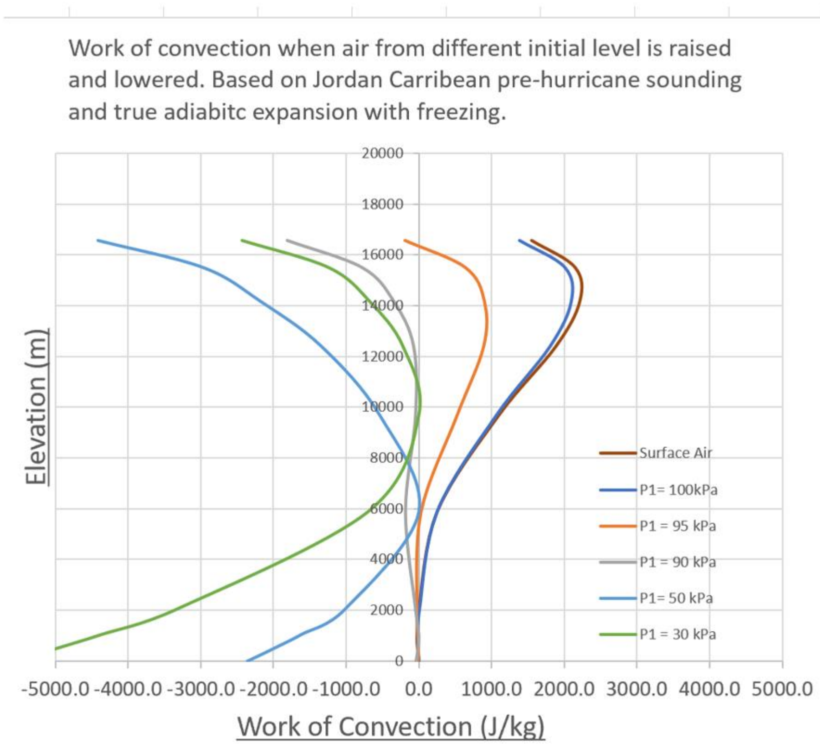


Fig. 5 Effect initial air level of on ezergy.

The ezergy of air initially at a pressure of less than 80 kPa is negative whether the air is raised or lowered. Moving mid or upper troposphere air either up or down *requires rather than produces* energy. As a result, the upper troposphere is stable. There is little turbulence outside the updraft areas which are much smaller than the surrounding downdraft area. In the upper troposphere, friction losses associated with horizontal flow are small because stability suppresses turbulence.

Fig. 6 shows a continuous process wherein surface air is raised in a vortex or expanding spiral. Internal kinetic energy can be large without violating conservation of energy provided the kinetic energy is recovered before the air leaves the system at low exit velocity. The high internal velocity provides centrifugal force and prevents the high external pressure from driving the surrounding air into the lower pressure air rising in the vortex, thereby suppressing mixing, turbulence and ezergy degradation.

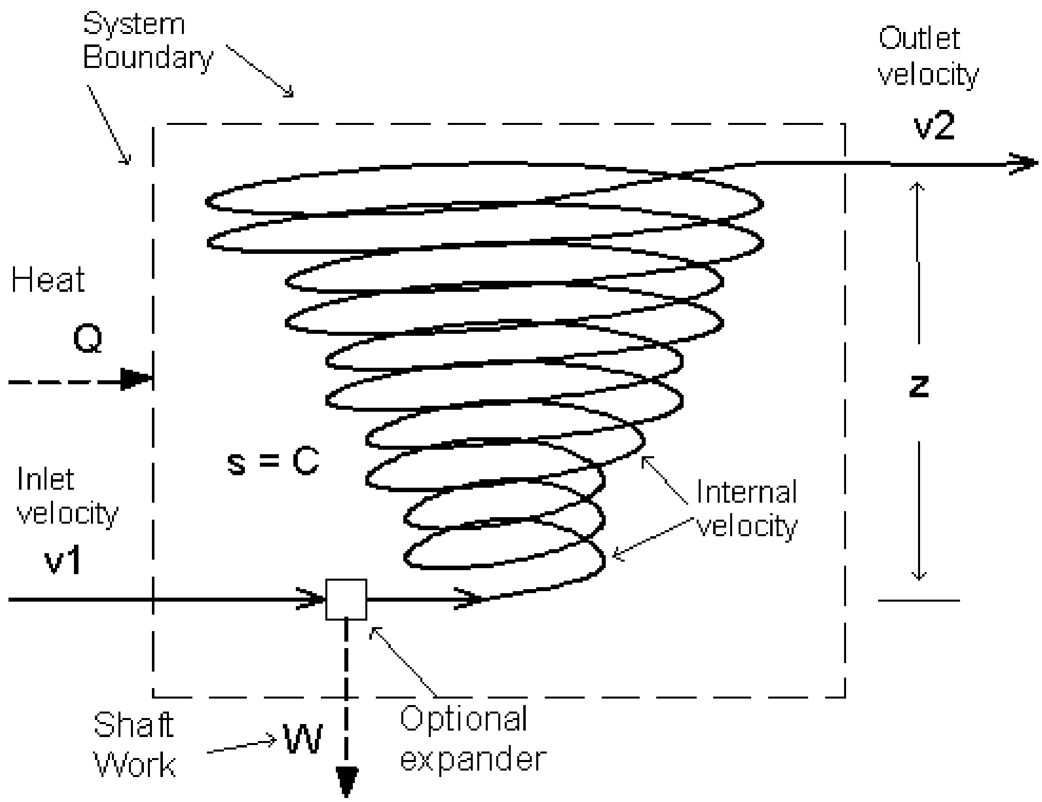


Figure 6. Continuous flow system with a spiral path.
High internal velocities do not affect the energy balance which only depends on external energy flows.

In a vortex, ezergy production takes place in an annulus of rising air at the radius of maximum tangential wind. The work is produced by the expansion of the air rising in the annulus. The kinetic energy of the vortex is provided by air rising in the annulus and not by the original angular momentum of the rising air. Conservation of angular momentum converts ezergy to tangential velocity. The intensity of the vortex is due to centrifugal force in the annulus preventing the rising air from being diluted by surrounding ambient air. Reference Vortex (V1) beautifully illustrates how a small tangential velocity at large radius becomes a high tangential velocity at small radius. The initial low speed rotation is not the energy source. Conservation of angular momentum requires that the tangential velocity increase as the air converges. The energy source is the air rising in the annulus.

The core of the vortex is dragged in solid rotation by friction. Some of the mechanical energy is transferred to the core by friction. The effect is the same as if some of the work produced by the turbine were used to drive a vertical axis pump impeller. Pulling down air from the troposphere would require ≈11000 J/kg, forced core rotation can not provide more than ≈5000 J/kg.

The core plays no role in energy production. In accordance with Willoughby (1998), the pressure reduction from the eyewall to the center will be taken as 30% of the overall pressure reduction. The pressure reduction produced by the rotating core can pull down air from the upper troposphere by a few kilometers but is insufficient to produce significant downward flow. Downward flow in the core would *require rather than produce* mechanical energy. Downward velocity in the core is insignificant compared to upward velocity in the annulus.

Margules (1903) used closed thermodynamic systems and showed that available energy is equal to reduction in total system enthalpy. The name enthalpy was coined by Heike Onnes in 1909. Open thermodynamic systems were not widely used before that time; they are now widely used in engineering but rarely used in atmospheric science. Bounded steady-state continuous processes can be used to understand unbounded non-steady state processes because, for the same process conditions, ezergy is the same for all reversible processes

Lorenz (1977) expanded the on the Margules system; he defined available energy as the difference between the actual enthalpy of the atmosphere and the enthalpy of a reference state. The reference state is minimum total enthalpy that could be achieved by rearranging the mass under reversible adiabatic processes. The reference state method is valid for dry air but not for moist air. Heating the atmosphere from below and cooling the atmosphere from above increase available energy. Convection decreases available energy. The atmosphere never comes close to the reference sate. The reference state is not reached so long as the ezergy of moving any air mass from one place to another is positive. The total enthalpy of the atmosphere goes up and down but is always far away from a reference state.

There have been numerous peer reviewed articles expanding on the reference state concept. Several papers have pointed out that CAPE is unable to account for observed tornado wind speeds of up to 130 m/s. Lilly (1969) suggested that downward core flow could play a role in tornado pressure reduction. Snow and Pauley (1984) concluded that the thermodynamic method is not physically sound because it could not produce tornado velocities. Randall and Wang (1990) showed that available energy of a column of air uniform in the horizontal direction is too small to explain observed tornado energy.

Tables 1a and 1b show the effect of surface air temperature and humidity on exergy and potential velocity for reversible and irreversible ascent. Potential velocities of greater than 130 m/s can be produced by raising 45 °C and 35 °C air in the reversible and irreversible cases respectively. Surface air temperatures can be over 35 °C, there is no need for axial downflow to explain axial pressure reduction. Ground temperatures in dust devil and tornado area can be over 50 °C. Heat can be transferred from dust to air further increasing air temperature.

Initial Surface Air Conditions			Work Potential - Reversible			
Temperature T_1 (°C)	Mixing Ratio M_1 (g-w/kg-air)	Relative Humidity U_1 (%)	Ezergy E_z, (J/kg)	Potential Velocity (m/s)	Potential Eyewall Pressure P_3 (kPa) ΔP 70%	Potential Eye Pressure (kPa) ΔP 30%
26.3	18.2	84.0	2215	65	99.0	97.9
29.4	18.2	68.9	**3033**	77	98.1	96.7
35	18.2	49.5	4762	97	96.3	94.1
35	22.0	60.5	7163	117	93.8	90.5
35 *	22.0	60.5	7985	125	92.9	89.3
45	18.0	27.7	7855	124	93.3	89.8
45	22.0	34.0	10001	140	91.2	86.7

Table 1a. Effect of initial air condition on Ezergy for reversible process. Based on Jordan pre-hurricane sounding. Initial pressure 101.51 kPa. Initial elevation, sea level, 0 m.
Final pressure and elevation 15 kPa and 14182 m
* Except for asterisk where final pressure and elevation 10 kPa and 16577 m.

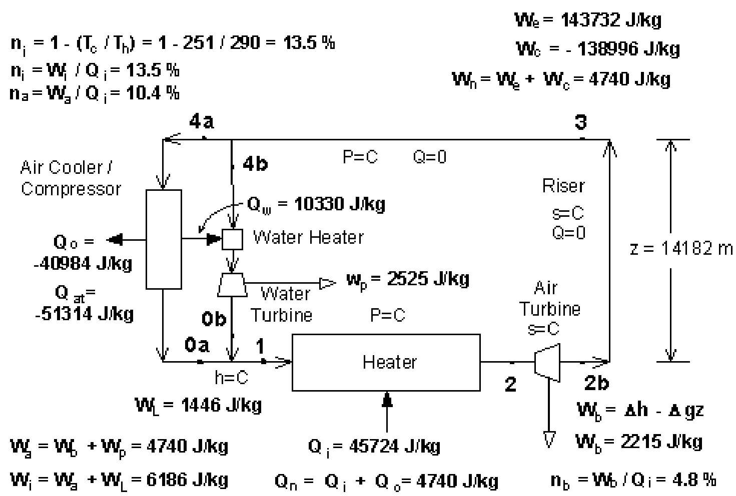
Initial Surface Air Conditions			Work Potential - Irreversible			
Temperature T_1 (°C)	Mixing Ratio M_1 (g-w/kg-air)	Relative Humidity U_1 (%)	Ezergy E_z, (J/kg)	Potential Velocity (m/s)	Potential Eyewall Pressure P_3 (kPa) ΔP 70%	Potential Eye Pressure (kPa) ΔP 30%
26.3	18.2	84.0	**3114**	78	98.0	96.5
35	18.2	49.5	6641	114	94.3	91.2
35	22.0	60.5	9541	137	91.3	87.0
35 *	22.0	60.5	11760	152	89.1	83.7
45	18.0	27.7	10843	146	90.3	85.5
45	22.0	34.0	13247	161	88.0	82.2

Table 1b. Effect of initial air condition on Ezergy. Irreversible expansion. Based on Jordan Pre-hurricane sounding. Initial pressure 101.51 kPa. Initial elevation, sea level, 0 m.
Final pressure and elevation 15 kPa and 14182 m.
* Except for asterisk where final pressure and elevation 10 kPa and 16577 m.

Bister and Emanuel (1998) showed that Irreversible increases potential intensity. Dissipating the exergy of 3114 J/kg, first line of Table 1b increases the air temperature by 3.1 °C has approximately the same effect as raising the temperature in lines 1-2 of Table 1a by 3,1 °C, 3033 J/kg.

3. Close cycle

Efficiency cannot be calculated for the open process of Fig. 2 and 3 because the heat input is zero. Closed ideal cycles will be used to calculate efficiency. The conditions in process 2-3 of the close cycle Figure 7 are the same as in the 15 kPa case of open system of Figure 2. The air and condensed water separate at point 4. During their separate descents, the air is cooled, and the water is heated so that they both arrive at the surface at 25 °C. The descending air is cooled in a reversible polytropic process by radiation to space and by heat transfer to the descending water. There is no evaporation during the descent; the air and water follow separate paths to permit thermodynamic analysis.



State	P (kPa)	T (°C)	r (g/kg)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	101.51	8.89	18.20	95.56	27098	0	27098
2	101.51	26.30	18.20	253.01	72822	0	72822
2b	98.99	24.17	18.20	253.01	70607	0	70607
3	15.00	-62.27	18.20	253.01	-70910	141516	70607
4a	15.00	-62.27	0.03	254.99	-62489	138991	76502
0a	101.51	25.00	0.03	84.04	25193	0	25193
4b	15.00	-62.27	18.17	-32.02	-8427	2525	-5902
0b	101.51	25.00	18.17	6.67	1903	0	1903

Figure 7. Close, reversible, atmospheric cycle
Adiabatic expansion with freezing.
No separation during ascent
Lapse rate of 6.153 °C/km

The cycle is per kilogram of pure air; time is irrelevant. The only unavoidable loss is mixing process 0-1. The temperature decreases from 25 °C to 8.89 °C in isenthalpic mixing process 0-1, during which a small part of the water evaporates. There is an increase in entropy and an unavoidable work loss in mixing process 0-1; the work loss (W_L) equal to $T\Delta s$ is 1446 J/kg. In a real process, where the moisture is provided by shallow updrafts, the work loss (W_L) could be slightly less. Heating process 1-2 is reversible; the air and the water are in equilibrium; and the heat source is at a temperature just slightly higher than the temperature of the saturated air water mixture.

"Overall Work" (6186 J/kg) is the sum of: air-turbine work (W_b = 2215 J/kg), water-turbine work (W_p = 2525 J/kg) and loss work (W_L = 1446 J/kg). "Overall Efficiency" is overall work divided by heat received 13.5 % (=6186/45724). Overall Efficiency equals Carnot efficiency, $n_i = (1 - T_c/T_h)$, where T_c (251 K) and T_h (290 K) are the average temperatures of the cold and hot source respectively. Ezergy is equal to the work of the air turbine ($W_b = E_z$). The potential energy of the condensed water (W_p) is assumed to leave the system but is not captured.

The heat received (Q = 45724 J/kg) is large compared to the ezergy of 2215 J/kg because the air has been dehumidified and must be re-humidified. The re-humidification water need not be the water that was separated. The re-humidification water can come from the sea via shallow updrafts. Dry air has a high affinity for warm sea water. As a result, oceanic boundary layer air typically has relative humidity of 60 to 80%.

Efficiency based on the work of the air turbine alone is 4.8 % (2215/45724). Fig.3 shows that adding heat to surface air increases ezergy by 27.2 to 30.5 % of the added heat. The reason for this high incremental efficiency lies in the metastable nature of moist air. The 15 kPa ezergies of 26.3 °C surface air with 85, 69.7 and 0 % relative humidity respectively are 2215, 0, and -12353 J/kg respectively. The corresponding surface air enthalpies are 72822, 64907 and 26423 J/kg. Surface air enthalpy of ≈64900 J/kg can be viewed as the *zero ezergy reference point.* The 38384 J/kg increase in enthalpy from 0 % to 69.7 % relative humidity is insufficient to render the ezergy positive. Ezergy efficiency is 5% of the total heat received and ≈ 25 % of the heat supplied at enthalpy above the enthalpy zero of ≈64900 J/kg.

Tropical ocean surface air ezergy is usually between -2000 and +2000 J/kg. Surface air is often close to the point where a small amount of heat is sufficient to release the energy production potential of heat received previously. Adding a small amount of heat can releases the ezergy potential of heat received by natural heating earlier. Adding heat to surface air increases ezergy (W_b) and has little effect on potential energy of condensed water (W_p) or loss work (W_L); the increase in overall work goes mainly to ezergy (W_b). As a result, incremental ezergy efficiency for heat received above the enthalpy zero could be as high as 10 %.

The close cycle of Fig. 7 can explain many features of the atmosphere better than atmospheric models. The total turbine work is equal to the heat input minus heat output (45724 – 40984 = 4740 J), and to the work of expansion minus work of compression (143732 – 138986 = 4740 J). The enormous works of expansion and compression are not obvious from atmospheric models. The work of expansion is 314 % (143,732 / 45724) of the heat received. The second law puts a limit on net work but does not limit the work of expansion. The ezergy is just 1.54 % (2215/143732) of the work of expansion. In the irreversible case, shaft actual work (W_a) is zero and heat out (Q_o) equals heat in (Q_i).

The potential energy of condensed water of 2440 J/kg is slightly larger than the ezergy of 2215 J/kg. The total turbine work is 10.4 % (4740/45724) of the heat received; the ezergy is 4.8% (2215/45724) of the total heat received.

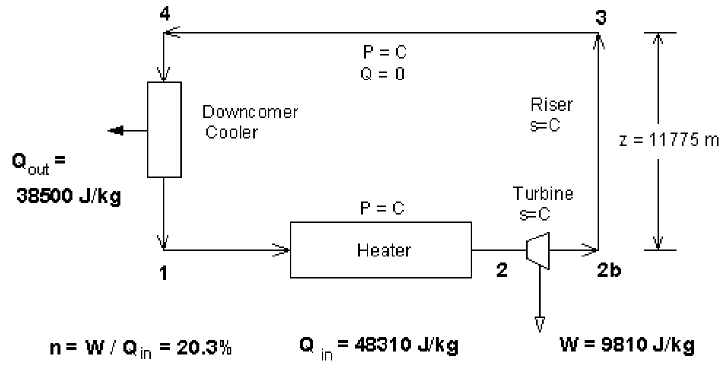
Subsidence occurs preferentially where the air is cold. Local subsidence compresses and warms underlying air thereby favoring remote subsidence. The subsidence occurs where the fluid is densest. Local subsidence would increase the 15 kPa elevation which would push the subsidence area away from the upflow area. Strong hurricanes produce no significant increase in the 15 kPa elevation in the neighboring region.

Energy is transported poleward mainly by work of compression rather than by sensible or latent heat. The descending air received 138986 J as work of compression which provides its increase in enthalpy of 87662 J plus its heat loss of 51314 J. The descent must be much slower than the ascent to give the air the time to cool by radiation to space. Radiating 41000 J/kg at 1.5 °C/d takes ≈27 days, corresponding to a subsidence velocity of ≈500 m/d (≈6 mm/s). An upward velocity of 3 m/s is ≈500 times the downward velocity corresponding to an ascent time of ≈1.3 h or ≈0.055 d. At a cooling rate of 1.5 °C/d, the descending air looses ≈41000 J/kg during its 27 days descent. The rising air only looses ≈80 J/kg during its ≈100 minutes ascent justifying the adiabatic assumption for the ascent process.

Moving 1 kg of surface tropical air to the polar troposphere can transfer 140,000 J of energy poleward. Accomplishing the same energy transfer by heat transfer would require cooling 14 kg of tropical surface air by 10°C and using this heat to warm the polar troposphere.

The role of work of compression in transporting heat poleward is seldom considered in atmospheric science. It is occasionally recognised that the energy of a column of air is increased by adding air at the top of the column while removing the same quantity from the bottom because moist static energy increases with elevation. Close reversible cycles are widely used to analyse industrial processes but have rarely been applied to the atmosphere, see Michaud (2000)

Conservation of mass requires that downflow equals upflow which requires that the downflow area be ≈500 times the area of the upflow area. Hadley and Ferrel circulation cells with updraft and downdrafts of roughly equal area are inconsistent with the requirement that the downdraft area be much larger than the updraft area. The upflow and downflow processes are very different. *Upflow produces work, downflow requires work.* Expansion produces work, compression requires work. Upflow is essentially an adiabatic process, downflow is a polytropic cooling process. Upflow is fast ≈3 m/s, downflow is slow ≈500 m/d. Upward velocity is approximately 500 times the downward velocity. Energy is transferred poleward and upward to the subsidence areas by work of compression. The location of upflow areas is not fixed. Hurricanes form in random locations and then wander. Additional information can be found at Michaud (1998, 2000 and 2012).



State	P (kPa)	T (K)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	100	290	60.14	16929	0	16929
2	100	338.1	214.14	65239	0	65239
2b	90.25	328.3	214.14	55429	0	55429
3	20	213.5	214.14	-59567	115395	55429
4	20	213.5	214.14	-59567	115395	55429

Carnot Efficiency based on average source temperatures

$$n_c = 1 - T_c / T_h = 1 - 251.7 / 314.0 = 19.8\%$$

Carnot Efficiency based on **log** average source temperatures

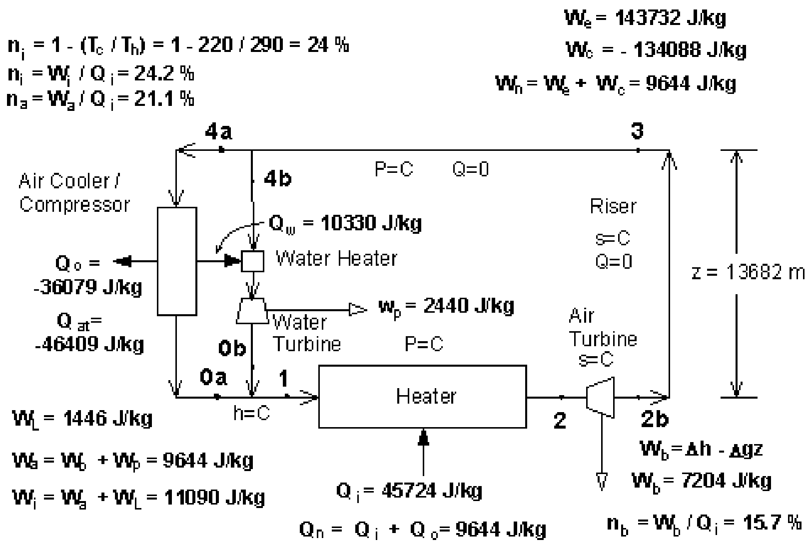
$$n_c = 1 - T_c / T_h = 1 - 248.8 / 313.1 = 20.5\%$$

Figure 8. Reversible close cycle - Pure air - no water, Doncomer cooling. Height based on lapse rate of 6.5 K /km

Single component systems are easier to understand than binary ones. Figure 8 shows a pure air single component system with a lapse rate is 6.5°C/km. The surface air receives sensible heat instead of latent heat. In both cases the raised air is at the temperature of the environment in state 3. The surface air is heated by 38°C and is extremely unstable. The tropospheric lapse rate is ≈6.5°C/km because the whole troposphere is cooled by radiation to space; without this cooling the lapse rate would be the dry adiabatic lapse rate of 9.8°C/km. The pure air system shows that the work is transferred to wherever in the circuit the flow is constrained. The turbine can be anywhere in the circuit. In an ideal process, ezergy is independent of turbine location.

Figure 9 shows a case where the 15 kPa surface is 500 m lower than in Figure 7. Lowering the 15 kPa surface by 500 m increases ezergy by ≈5000 J/kg. The elevation of the 15 kPa pressure is approximately 1000 m lower at the poles than in the tropics. A 500 m reduction corresponds to mid-latitude elevation. At 85 % relative humidity, the air temperature required to achieve an ezergy of 2215 J/kg is 26.2 °C in the tropics and only 21.5 °C in mid latitude because the 15 kPa air is 500 m lower. The appendix suggests the name *epergy* for exergy based on the use of a lower than local upper elevation. The “p” stands for poleward.

Raising tropical air in high latitudes where geo-potential heights are lower can produce more mechanical energy than doing so locally thereby increasing atmospheric efficiency. Satellite videos of tropical cyclones occasionally show hurricane exhaust air streaming towards colder regions. Descent in high latitude could contribute to hurricane intensity. Horizontal distance is not an impediment because friction losses can be small.



State	P (kPa)	T (°C)	r (g/kg)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	101.51	8.89	18.20	95.56	27098	0	27098
2	101.51	26.30	18.20	253.01	72822	0	72822
2b	88.36	19.36	18.20	253.01	65618	0	65618
3	15.00	-62.27	18.20	253.01	-70910	136527	65617
4a	15.00	-62.27	0.03	254.99	-62489	134087	71598
0a	101.51	25.00	0.03	84.04	25193	0	25193
4b	15.00	-62.27	18.17	-32.02	-8427	2440	-5987
0b	101.51	25.00	18.17	6.67	1903	0	1903

Figure 9. Close, reversible, atmosheric cycle
Adiabatic expansion with freezing, No separation,
Effect of reducing z4 by 500 m. Lapse rate 6.378°C/km..

Ezergy can be calculated in several ways:

1) Reduction in moist static energy Eq. (2).
2) Heat received multiplied by Carnot efficiency based on average hot and cold source temperatures minus the potential energy of condensed water and the mixing loss.

$$E_Z = \Delta H - \Delta gz = Q_i\left(1 - \frac{T_c}{T_h}\right) - W_p - W_L \qquad (4)$$

3) Acceleration of buoyant air (CAPE).
4) Reduction in pressure at base of a buoyant air column per Holland (1997).

4. Sea water spray – Tropical cyclones and waterspouts.

Tropical cyclones are driven by surface enthalpy fluxes. Figures 10 and 11 and Table 2 show the effect of spraying surface air with sea water. Air holds more water vapor at reduced pressure. For a given temperature and relative humidity, mixing ratio increases with decreasing pressure. The mixing ratio for 26 °C air with 90 % relative humidity is 19.14 g/kg at 101.51 kPa and 20.25 g/kg at the reduced pressure of 96.12 kPa, corresponding to ideal works of 2760 and 4790 J/kg respectively. For the same temperature and relative humidity, reducing pressure by just 5.4 kPa increases available work by 73 %. In Figure 10, work production is enhanced by spraying the air with sea water at the low pressure downstream of the turbine instead of at the higher pressure upstream of the turbine. Supplying the heat at lower pressure permits the use of the heat content of water at lower temperature. The available work with sea spray will be called *evergy*, where "*v*" stands for "*very-energetic".*

Figure 10 and Table 2 shows the effect of sea water on *evergy*. Air containing fine water droplets is always saturated and has a relative humidity of 100 %. Otherwise, the vapor pressure of the liquid water in the droplets is greater than the vapor in the air. The water and the air come to equilibrium within seconds, Sroka and Emanuel (2021). The temperature of the saturated air increases with the water-to-air mass flow ratio. At very high water flow, the temperature of the saturated air approaches the temperature of the sea water.

Producing moist air would requires more spray if the initial surface air temperature or relative humidity were lower. The effect of low initial temperature can be compensated for by increasing the water spray. A small fraction of the spray evaporates, typically 0.3 %; the remaining 99.7 % falls back into the sea at the temperature of the saturated air. The heat of evaporation is provided by the reduction in the sensible heat of the part of the spray which does not evaporate and falls back in the sea. The enthalpy transfer process is an equilibrium process rather than a surface-to-air energy transfer process. There is no need for heat transfer or drag coefficients.

The mass and heat transfer from spray-to-air is much faster than from the sea-surface-to-air because drops have more surface area per unit mass than the surface of the sea. The affinity of air is zero for water at the dew point temperature of the air and increases rapidly with water temperature. Enthalpy transfer between water and air increase with affinity and with contact area.

Several indices of hurricane potential intensity have been used. Emanuel (1997) used maximum velocity; Holland (1997) used minimum central surface pressure. The Ezergy approach is based on energy conservation; it provides ideal work, pressure at the base of the eyewall updraft, and maximum velocity but does not provide the central pressure. For purpose of comparison with Holland, the pressure reduction from the eyewall to the center will is taken as 30% of the eyewall pressure reduction in accordance with Willoughby (1998). The Holland and Emanuel methods are more calculation demanding than the energy conservation approach.

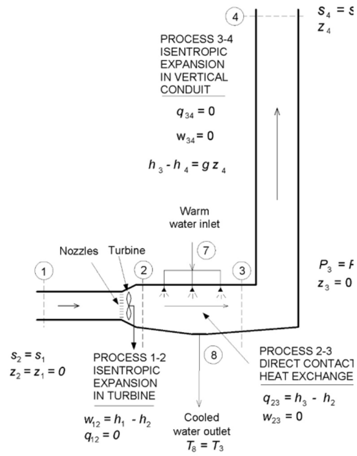
WORK TO SPRAY SENSITIVITY

Basis:

Jordan Caribbean hurricane sounding
P_1 = 101.51 kPa, T_1 = 27 °C
U_1 = 75%, M_1 =16.95 g/kg
SST = T_7 = 28 °C
True adiabatic with ice.
W_b = W_{12} = Turbine Work (Ezergy)
P_3 = Updraft base (eyewall) pressure

Observations

1. Ezergy and P_3 reduction increase with state 3 temperature and %RH.
2. Ezergy increases with water flow.
3. Sensitivities are 25% higher when the air is raised to its level of neutral buoyancy.
4. Sensitivities to water flow would be 30 to 50% higher when flow is irreversible .



P_4(kPa)	z_4(m)	T_3(°C)	U_3(%)	P_3(kPa)	M_3(g/kg)	W_b(J/kg)	F_7/F_3(kg/kg) REV.	IRR.
Without water spray								
15	14180	25.49	80.75	99.73	16.95	**1564**		
With water spray								
15	14180	25	90	98.13	18.64	**2983**	0.28	0.12
15	14180	25	100	95.61	21.28	**5258**	1.09	0.68
15	14180	26	90	96,12	20.25	**4791**	0.86	0.51
15	14180	26	100	93.73	23.10	**6981**	2.50	1.67
10	16577	26	100	91.78	23.60	**8797**	2.86	1.81

Sensitivites

$\Delta W_b/\Delta U_3$ = 281 (J/kg)/% (at T_3 = 25)
$\Delta W_b/\Delta U_3$ = 219 (J/kg)/% (at T_3 = 26)
$\Delta W_b/\Delta T_3$ = 1760 (J/kg)/K (at constant U_3)
$\Delta W_b/\Delta T_3$ = 2200 (J/kg)/K (at U_3 = 100%, P_4 = 10 kPa)

$\Delta W_b/\Delta(F_7/F_3)$ = 2810 J/kg (at T_3 = 25°C, reversible)
$\Delta W_b/\Delta(F_7/F_3)$ = 1340 J/kg (at T_3 = 26°C, reversible)
$\Delta W_b/\Delta(F_7/F_3)$ = 3120 J/kg (at U_3 = 90%, reversible)
$\Delta W_b/\Delta(F_7/F_3)$ = 1220 J/kg (at U_3 = 100%, reversible)

Figure 10. Effect of sea water spray on ideal work (Evergy)

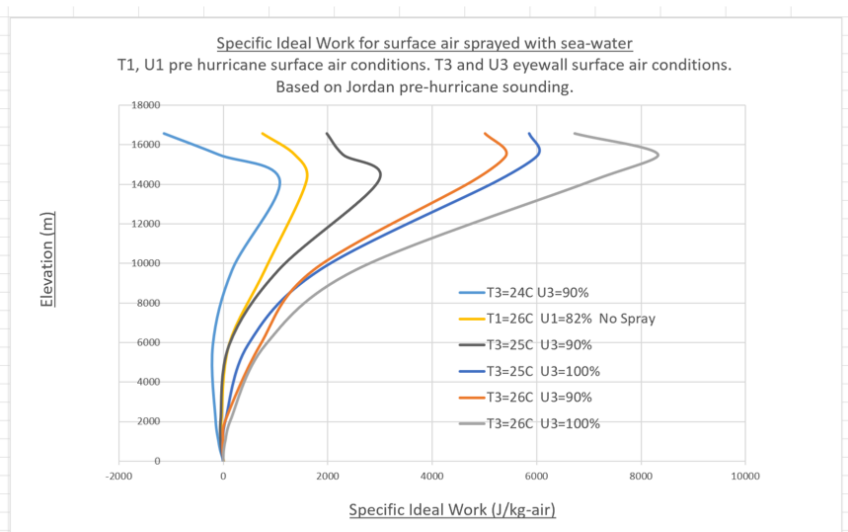


Figure 11. Effect of water spray on ideal work (Evergy). Curves show effect of eyewall temperature and relative humidity.

Sea Surf. Temp SST	Conditions at Updraft Base			Potential Intensity					Spray to Air Mass Flow Ratio
T_7 (°C)	T_3 (°C)	U_3 (°C)	M_3 Mixing Ratio (g/kg)	E_v Evergy (J/kg)	Velo-city (m/s)	P_3 (kPa) ΔP 70%	P_c (kPa) ΔP 100%	P_c (kPa) Holland Fig. 13	F_7/F_3 kg-w / kg-a
Without sea water spray									
N/A	27	75	16.95	1560	55	99.7	99.0		0
$T_7 - T_3$ = 1 °C U_3 = 90 % per Holland (1997)									
25	24	90	17.1	1090	46	100.3	99.7	100	N/A
26	25	90	18.6	2980	76	98.1	96.7	98	0.53
27	26	90	20.3	4790	96	96.1	93.8	95	1.23
28	27	90	22.0	6500	112	94.2	91.1	92	1.94
29	28	90	23.8	8110	114	92.5	88.7	88	2.64
30	29	90	25.8	9120	135	90.9	86.4	87	3.34
T_7 = 28 °C U_3 = 90 %									
28	24	90	17.1	1090	46	100.3	99.7		N/A
28	25	90	18.6	2980	76	98.1	96.7		0.28
28	26	90	20.3	4790	96	96.1	93.8		0.86
28	27	90	22.0	6500	112	94.2	91.1		1.94
T_7 = 28 °C U_3 = 100 %									
28	24	100	19.6	3420	81	97.6	96.0		0.40
28	25	100	21.3	5260	100	95.6	93.1		1.09
28	26	100	23.1	6980	116	93.7	90.4		2.50
28	27	100	25.0	8590	128	92.0	87.9		6.75
28	27.5	100	26.0	9350	133	91.2	86.8		15.2

Table 2. Effect of sea water spray on evergy. Based on Jordan sounding. P_1 = 101.51 kPa, T_1 = 27 °C, U_1 = 75 %, M_1 = 16.95 g/kg, P_4 = 15 kPa, z4 = 14182 m. Symbols are defined in Figure 10.
Sensitivity of central pressure to updraft temperature: 2.7 Pa/K, versus Holland 3.3 kPa/K, versus Emanuel 1.05 kPa/K.
Sensitivity of central pressure to updraft relative humidity: 0.36 kPa/%, versus Holland 0.48 kPa/%, versus Emanuel 0.62 kPa/%.

In the 26 °C 90 % relative humidity case, the water spray increases mixing ratio from 16.95 to 20.25 g/kg and increases available work by a factor of 3 from 1564 to 4790 J/kg. The *evergy* is 4790 J/kg. In every case of Table 2, the change in moist static energy in process 3-4 is zero. P_3 is the pressure for which the ezergy in process 3-4 is zero. The *ezergy* of raising 96.1 kPa 26 °C 90 % relative humidity eyewall air to the 15 kPa level is zero. The work of expansion is transferred from process 3-4 to process 1-2. The *emergy* is the work of expansion from distant surface pressure to eyewall surface pressure P_3. The *emergy* of expanding 101.51 kPa air to 96.1 kPa is 4790 J/kg. The ideal work is transferred to the turbine where the flow is restricted.

Rising air conditions are important because most of the work of expansion is produced during the upflow and eventually used to raise the air and to drive the turbine located at grade. Holland (1997) recommended using updraft temperature 1 K colder than SST and an updraft relative humidity of 90% since the condensation level in hurricanes is typically around 500 m. Table 2 shows that Holland's recommendations are appropriate. Minimum axial pressure P_a agree with Holland (1997) figure 13. Sea-surface temperature at the eyewall can be 1 °C lower than pre-hurricane sea surface temperature.

The agreement between Holland's axial pressure reduction in his Figure 13 and the axial pressure reduction calculated from the present energy conservation approach is amazing. The two methods are equivalent. Holland calculates axial pressure from hydrostatics. Evergy calculates axial pressure from energy conservation. Holland uses pseudo-adiabatic expansion; the present *evergy* method uses true-adiabatic expansion with freezing of condensed water. Holland uses an arbitrary axial relative humidity profile; the present evergy method assumes that the pressure drop from the eyewall to the axis is 30% of the overall pressure drop.

Sea surface temperature is by far the dominant contributor to hurricane intensity. The effect of surface air temperature and humidity and of upper level elevation are minor compared to the effect of sea surface temperature.

The 90 % relative humidity rising air could be a combination of saturated air from low elevations plus unsaturated air from higher elevations, such as 25°C 80 % relative humidity air from an elevation of 50 m where the spray has completely evaporated. Spray decreases rapidly with height; spray-to-air mass flow ratio decreases with height. The rising air can be a combination of air from different elevations and need not be saturated. For 26°C water temperature, the temperature of the saturated air could be 26°C at the at 1 m elevation, 25°C at 5 m, 24°C at 10 m respectively because the saturated air temperature decreases with spray to air ratio. Table 2 shows that producing saturated air 1 °C colder than sea surface temperature requires water to air mass flow ratios of 1.5 to 3.3 kg-w/kg-air. The flow ratio increases with water temperature. A 1 °C temperature difference could require a flow ratio of 1 to 10 depending pre-hurricane air temperature. The increase in the required flow ratio at higher SST may explain the flattening of axial pressure drop at high SST in Holland Figure 13.

The humidification of converging air by sea spray starts at high radius as soon as there is significant spray. The temperature of the saturated air and the evergy increase with water flow.

The effect of spray is cumulative. In the 28 °C SST 100 % relative humidity section at the bottom of Table 2, increasing the saturated air temperature from 26 to 27 °C requires an additional water flow of 3.63 kg-w/kg-a. Humidification takes place as long as part of the circulation is in a heavy sea spray area. As a result, hurricanes intensity winds can persist well after the eyewall arrives over land.

Emanuel (1986) developed an equation for maximum hurricane wind speed which he called potential intensity. His equation has been used to produce charts of maximum hurricane wind velocity. Emanuel calculated ideal work as a product of surface heat flux and of efficiency. The surface heat flux term uses enthalpy and drag coefficients. He claims that the atmosphere is a Carnot engine receiving heat at sea surface temperature and giving up heat at the tropopause temperature. His cycle diagram shows that the cooling occurs at the tropopause and not throughout the decent process as shown in Figure 7. Emanuel's efficiency is the Carnot efficiency based on the temperatures at the bottom and at the top of the troposphere. Emanuel's efficiency is too high because the heat is given up at the average temperature and not at the top temperature of the troposphere. Renno (2008) used the average temperature of the troposphere as the cold source temperature.

Furthermore, the Emanuel efficiency methods does not recognize that surface air can have potential to do work without heat transfer from the sea and that ≈ 60 % of the work is used to raise water or is lost due to mixing. Emanuel used efficiencies as high as 33 % and 50 % for reversible and irreversible flow respectively, Bister and Emanuel (1998). The Holland method and the present approach inherently consider potential energy of condensed water, of mixing losses and of the exergy of the air prior to it being sprayed. Table 2 sensitivities show that the results of the current energy approach are closer to those of Holland than to those of Emanuel.

The present energy approach yields efficiencies of 5 to 10 %. Emanuel's surface heat flux is too low because the heat transfer is via an equilibrium process and not via a heat transfer process. Emanuel's intensity estimates are on the low side; hurricane intensity occasionally exceed his potential intensity. Holland's intensity estimates on the high side can be explained by dry air dilution at high elevation or by frictional losses.

Hurricane intensity can be calculated with steady-state process simulators. PRO/II from AVEVA is a steady-state process simulator for process engineers in chemical industries. It includes a component library, thermodynamic properties, and units of operations such as expanders, flash drums, mixers, custom calculations, and controllers which can be linked. It performs steady-state mass and energy balance calculations such as isentropic expansion of moist air. PRO/Ii provides a wide choice of thermodynamic properties options. Links to PRO/II simulations can be found in the reference section. PRO/II is a drag and drop easy to use program. PRO/II thermodynamic properties do not support ice phase. As a result, the calculated work is slightly lower than in the present calculations. Energy calculations are per unit mass - per kilogram of air in the previous examples, and in per tonne per second in the PRO/II calculations. The atmosphere is not a steady-state system, but PRO/II can be used to explain the energy of storms by viewing the atmosphere as consisting of reservoir joined by steady-state flow processes.

The PRO/II links in the reference section show that:

- The work increases with the temperature and with the mixing ratio of the air.
- The work increases with the quantity and temperature of the water spray.
- The air and water leaving the flash drum are in equilibrium and at the same temperature.
- The air leaving the top of the flash drum is saturated.
- The temperature of the air leaving the flash drum increases with water flow and water temperature.
- The efficiency of the first expander can be decreased from 100 % to 0 % to check the effect of irreversibility.
    - For heat provided by the air inergy is ≈30 % higher than its ezergy,
    - For heat supplied by water spray inergy is only ≈2 % higher than its ezergy.
- Mixing unsaturated air in the rising saturated air reduces work.

If any two properties of a two components system are known, all other properties can be determined. There is no need to use properties such as equivalent or virtual temperatures, or velocity, or density.

5. Conclusion

Margules abandoned meteorology because his thermodynamic approach was not well received. In his last paper which received little attention, Margules (1906), he wrote:

- I hold vertical movement under the influence of gravity to be the essential cause of storms.
- The energy source is not to be found in gradients but in the sinking of colder air and the rising of warmer and moister air. The energy potential of horizontal pressure difference is very small.
- One could gain a closer understanding, when better method than presently known, for the handling of aerodynamic problems are found.
- For reasons I will not go into I am leaving meteorology.

Margules (1906) calculated the maximum work produced when saturated air is raised for one case in which he obtained results in agreement with the approach of this article.

Engine efficiency is calculated by following a fluid through idealized cycles wherein properties such as pressure, temperature, entropy, enthalpy, and composition are conserved. The flow is constant. Flow and process are specified; heat, work and efficiency are calculated. Unit mass calculations make results easy to compare.

Atmospheric models calculate future trajectories based on initial conditions and on forcings. Trajectories are not specified; there are many trajectories that satisfy the equation of motion including every weather pattern that has ever occurred. Hurricane models produce a spaghetti of trajectories. There is mixing of fluid with unrelated properties in unspecified proportions. The flow is different in every case making result difficult to compare. Atmospheric model performance is judged by how well they predict future weather. Coefficients can be adjusted to make results agree with observations. Calculating efficiency from models is virtually impossible.

The energy of hurricanes is due to enthalpy transfer from the underlying warm sea. Wind energy is often attributed to horizontal and not to vertical gradients. For example, Kleidon (2012) estimated the total atmospheric energy potential at ≈6000 TW most of which is unavailable because it is dissipated during atmospheric convection. The Lorenz (1967) reference state approach adds little of value and provides no information about where the work is produced. There is no need to consider the effect of subsidence on upper-level elevation because the subsidence occurs over a wide area and mostly well away from the updraft.

The ezergy approach shows that the available work can increase the kinetic energy of the rising air itself or produce other forms of mechanical energy and that the energy can be captured by constraining the flow with an expander located at grade. The thermodynamic basis is well established. Engineering tools such as PRO/II were designed for use on any continuous thermodynamic process and could be applied to the atmospheric process but have not been.

There is an urgent need for clean renewable energy. The atmospheric upward convection process could be harnessed to produce abundant and clean renewable energy. There are many examples of human produced vortices, Michaud (V1 to V6). Energy production will require large costly prototypes because the vortex must extend over 0.5 km to start the release of latent heat and over 5 km to produce significant ezergy. The vortex must be controllable and stable. There are many possible configurations. Michaud (1975, AVE2007, AVE2021). A concerted development program would quickly find out what works. We cannot control natural storms, but we can learn to produce well controlled atmospheric vortices.

Chemical and power engineers welcome contributions from other disciplines and realise that experience acquired in other disciplines can improve process performance. One learns faster from experience, including failures and success, than from peer reviewed papers; one finds out quickly if ideas work and improves on them at the next opportunity. Like with other inventions Ideas for improvements can come from anyone. Ideas that work are quickly identified and selected.

"Silo mentality can create counterproductive competitions, and hinder communication, creative thinking and boundary-spanning collaboration. Climate leaders need to talk and forge productive working relationships with people holding differing perspectives, knowledge and interests". Bateman and Mann (2016).

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Appendix

PROPOSED FREE ENERGY NAMES

Free energy is the maximum work that can be made available by bringing a fluid to equilibrium with an environment. The energy is **free** because there is no need to provide costly heat. Free Energy is real work and can become shaft work. There are several kinds of free energy; distinctive names for them would be useful.

Existing free energy name

Exergy (E_x) is the maximum work that can be made available when a fluid is brought reversibly to pressure and temperature equilibrium with an environment.

$$E_x = A = -\Delta H + T_0\ \Delta S - g\Delta z \qquad (A1)$$

where ΔH and ΔS are the difference in enthalpy and entropy of the fluid between its initial and final state, where T_0 is the temperature of the final environment, and where Δz is the change in elevation. There is no need for a solver since the temperature, enthalpy and entropy of the fluid in the initial and final state are known. Discovered by Willard Gibbs in 1873 and given the name "Free Energy"; renamed **Exergy** by Zoran Rant, in 1951. The usual symbol for ezergy is ***"A"***. The $g\Delta z$ term is zero in processes where there is no change in elevation.

Proposed New free energy names

Ezergy (E_z) is the maximum work that can be made available when it is brought to pressure equilibrium with an environment via a reversible adiabatic (S=C) process. The "***z"*** stands for change in elevation (Δz).

$$E_z = -\Delta H - g\Delta z \qquad (A2)$$

where ΔH is the reduction in the enthalpy of fluid moved at constant entropy from the initial to the final pressure. Final temperature and enthalpy are calculated from known final pressure using a solver. **Ezergy** is always less than **exergy** because a Carnot engine producing work could be used to bring the moved fluid to temperature equilibrium with the final environment, irrespective of whether the temperature of the raised air is initially higher or lower than the temperature of the final environment. Ezergy (E_z) is independent of the temperature of final environment. Exergy (E_x) is dependent of the temperature of final environment. Ezergy does not include the potential energy of condensed water because it is not available at the initial location. Ezergy is the maximum available work and not the maximum work because it does not include the potential energy of condensed water.

Emergy (E_m) is the maximum work that can be produced when there is no change in elevation such as in an ideal gas turbine. The "***m"*** stands for same (**m**ême), no change in elevation ($\Delta z = 0$), and also for Emmie, the carer, in Geinor Styles' musical "The Eye of the Storm".

$$E_m = -\Delta H \qquad (A3)$$

In Figures 2 and 3, turbine emergy is equal to system ezergy. Ezergy can produce shaft work at grade. Ezergy is much smaller than work of expansion because most of the work of expansion is needed to raise the air and its water content.

Evergy (E_v) is the maximum work that can be produced, based on specified temperature and relative humidity at turbine outlet pressure and temperature, via a reversible adiabatic (*S=C*) process. The "***v"*** stands for ***v****ery* energetic. For the same temperature and relative humidity, evergy is larger than ezergy because air hold more vapor at reduced pressure.

Epergy (E_p) is the maximum work that can be produced when fluid is brought reversibly to an environment where pressure surfaces are lower than directly overhead, which is generally a more poleward location. The "*p*" stands for **p**oleward.

Imergy (E_i) is the work produced and dissipated in a fully **i**rreversible moving process.

Subscripts and Defaults.

Free energy type can be further specified with subscripted numbers in parentheses. Default shown may be omitted.

$E_{z(\text{s-15})} = E_z$ Ezergy of surface air raised to 15 kPa level.
$E_{z(\text{s-e})} = E_x$ Ezergy of surface air raised to its level of neutral buoyancy (LNB) -
$E_{v(26\text{-}90\text{-}15)} = E_v$ Evergy of 26°C, 90% relative humidity air at the reduced pressure at the base of the updraft
$E_{p(500)} = E_p$ Epergy of air surface sir raised to an environment where the 15 kPa surface is 500 m than directly overhead.