Energy From Human Air

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Abstract

The atmosphere is an engine wherein heat is converted to mechanical energy. It is heated from the bottom by solar radiation and cooled from above by infrared radiation to space. The heat is carried upward by convection. There is a potential for producing work because the work of expansion of warmed rising surface air is greater than the work of compression of descending cooled air.

Steady-state open and close thermodynamic processes are used to analyse the atmospheric heat to work conversion process. The *total energy equation approach* explains the energy of tornadoes and of hurricanes and is compatible with the convective available potential energy (CAPE) approach. The technique is illustrated using the Jordan mean hurricane season West Indies sounding.

The ideal work produced when oceanic tropical surface air is raised from the surface to the tropopause is typically 1000 to 3000 J/kg. Ideal work can be calculated from the initial and final conditions of raised air; there is no need to consider intermediate environmental conditions. The low frequency and small area coverage of deep convection is due to convective inhibition (CIN), and to entrainment of dry ambient air in the updraft. In vortical flow, centrifugal force reduces entrainment.

Sea-spray is responsible for hurricane intensity and for the associated sea cooling. Heat is transferred from sea to air by spray. Spray drops are quickly cooled to the wet bulb temperature of the air. Approximately 99.5 % of the spray falls back in the sea at temperatures up to 5 °C colder than the sea surface temperature; thereby, transferring enormous quantities of heat from sea to air. Sea-spray produces saturated air whose temperature increases with the spray-to-air mass ratio. Ideal work increases by about 1100 J/kg °C of surface air wet bulb temperature. There is a potential for converting 25 % of heat added to humid surface air to mechanical energy. The contributions to sea surface cooling of surface to air heat transfer and of upwelling of cold water are minor compared to those of spray.

The focus of the article is on the thermodynamics of the atmospheric process, on mechanical energy production. The conclusions are applicable to the atmosphere in its natural state and to processes for harnessing its energy such as the solar chimney and the atmospheric vortex engine (AVE). This article does not discuss AVE implementation, which have been done elsewhere, Michaud (1975, 1999). The article is based on atmospheric science and on engineering experience; references are not limited to the peer reviewed literature.

1. Introduction

The determination of efficiency is the fundamental problem of atmospheric energetics, Lorenz (1967). Estimates of atmospheric efficiency range from over 12 %, based on the Carnot efficiency based on the average temperatures at which heat is received (290 K) and given up (255 K) to less than 1 % based on dissipation, on models, on observations, and on atmospheric poleward heat transport. 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 work 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 thermal 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 energy at the higher 12 % efficiency. The thermodynamic total energy equation approach, widely used in engineering. is more appropriate than computational fluid dynamics models (CFD).

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 heat carried upward by infrared radiation from the lower atmosphere to space do not contribute to work production because the heat is not carried upward by convection; there is no associated expansion-compression. .

A photovoltaic solar power plant requires a collector area of 200 km^2 to produce 2 GWe. Atmospheric work production can be concentrated in a small area. 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. AVE's could convert 25 % of low temperature heat to work. A tornado with vortex diameter of 300 m can produce ≈2 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 could produce mechanical energy from heat sources with temperatures as low as 25°C.

Section 2 shows that the mechanical energy produced when warm humid air is raised can be calculated from energy balance in a steady-state open thermodynamic system and that the energy can be transmitted to where the flow is restricted. Section 3 investigates the effect of surface air temperature and humidity on energy production and shows that the *incremental-efficiency* (IE), the increase in mechanical energy production per unit of heat supplied, can be 25 to 30 %. Section 4 uses close cycles to show that the overall efficiency can be 12 % of the total heat input. Section 4 also shows that energy is transferred upward and poleward mainly by work of compression. Section 5 shows that spraying surface water can increase specific work from 2000 to 10000 J/kg. Section 5 shows that sea-water spray is responsible for hurricane intensity and for the associated sea cooling. Section 6 shows that atmospheric energy production can be calculated with easy-to-use drag-and-drop engineering steady-state process simulators.

2. Steady-State single input single output system

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 heat. The work is produced from the pre-existing natural heat content of humid surface air.

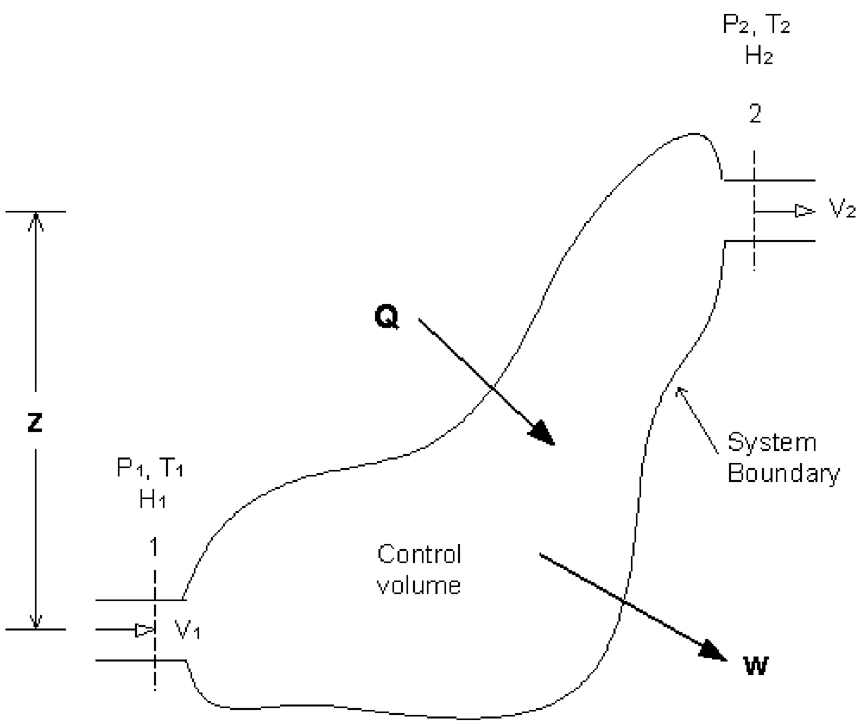


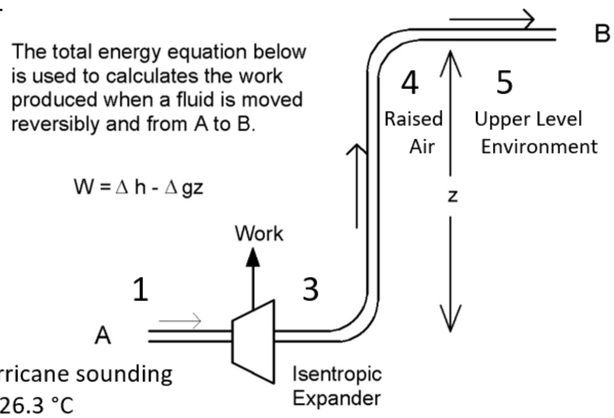
Figure.1 Energy balance for open continuous steady-state thermodynamic system,with one inlet and one exit.
Based on Smith and Van Ness Figure 2.6

Fig. 1 shows a thermodynamics system applicable to any open steady-state, continuous flow, single-input 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:

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

where: *W* is the work leaving the system, *Q* is heat received, *H* is enthalpy, *g* is acceleration of gravity, z is height, and v is velocity. See Smith and Van Ness (2001) "Introduction to Chemical Engineering Thermodynamics" chapter 2, Eq. 2.32. The energy unit can be in Joules/kg-pure air; Joules/kg-substance; Watts per unit of flow; or Watts. In this article Joules per kilogram of pure air including the contribution of water content in any phase is used. Having a constant air mass of 1 kg of pure air simplifies calculations and facilitates case comparisons.

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.

Maximum *work of buoyancy* (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 air. The contribution of the water content (*m*) of the air in any phase must be included in the enthalpy term (ΔH) and in the potential energy term ($g\Delta z$). This ideal work will be called ***ezergy*** (E_z) to highlight change in elevation (Δz). *Ezergy is equal to the decrease in enthalpy minus the increase in potential energy of the raised air*, and 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.

In the atmosphere, the mixing ratio for water in all phases (m) has a maximum value of about 0.03 kg-w/kg-air. W_b stands for work of buoyancy and is just a different symbol for E_z; W_p stands for potential energy of water in any phase. The potential energy of the water, *mgz,* is not shown explicitly in (2) because it is included in the $g\Delta z$ term. The condensed water does not separate from the rising air.

Figure 2 shows an example of an ideal open reversible adiabatic process moving air from the bottom to the top of the troposphere. Figure 2 is based on the Jordan (1958) mean West Indian hurricane-season sounding. Work degradation through friction is negligible because velocity can be low in ideal processes. There is no heat transfer because the conduit is perfectly insulated. A constant entropy expander or turbine with a shaft is required to get the mechanical energy out of the system.

The three cases of Figure 2 show the effect of final pressure on ideal work. *Ezergy* peaks at ≈2215 J/kg for surface air raised to the 15 kPa (14182 m) level. An adiabatic reversible process is a constant entropy (*S*) process. From known initial air conditions and final pressure, the final temperature for a constant entropy process can be calculated using a solver. Ezergy can then be calculated from the known initial and final enthalpy and the change in elevation. There is no need to consider density, buoyancy, potential, equivalent or virtual temperatures. Knowing three properties of a two components system at equilibrium permits calculation of all its other properties.

Willard Gibbs showed that the *ideal work*, for a fluid brought reversibly to full equilibrium with a different environment with reversible heat transfer is:

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

See Smith and Van Ness (2001) Eq. 5.24 and 5.27. Gibb's *ideal work* is now called *exergy for which* "*A*" (from the German *Arbeit*) is the standard symbol. T_o is the temperature of the final environment. ΔH is the difference between the enthalpy of the fluid between its initial and final state. ΔS is the difference between the entropy of the fluid between its initial and final state. There is no need to use a solver to calculate 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 reversibly. The third, 12.64 kPa case, of Figure 2 shows that *exergy* and *ezergy* are identical for air raised to the level of temperature equilibrium, the level of neutral buoyancy (LNB), because there is no need to transfer heat via a Carnot engine to reach temperature equilibrium. The 15 kPa case shows that *ezergy* peaks near the 15 kPa level. Exergy keeps increasing well past the 15 kPa level. Ezergy has a maximum; exergy keeps increasing.

Exergy is the maximum work that can be produced when a fluid is brought reversibly to full equilibrium with an environment. Gibbs used the names *Ideal Work* and *Free Energy. Ideal work* and *free energy* have a variety of meanings. Rant realized the need for an unambiguous name and coined the name *exergy*, see appendix of 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 an unambiguous name for this property; it is proposed that it be called *ezergy* (E_z) to indicate that there is a change in elevation (z) consistent with the Rant naming system.

Exergy and *ezergy* production usually requires that the final pressure be lower than the initial pressure. *Ezergy* is freer than *exergy* because there is no need for the Carnot engine to transfer heat. Environments suitable for producing energy from surface air are found in the upper troposphere. This article proposes names, inspired by the Rant naming system, for other kinds of mechanical energy. These names are summarised in appendix A.

Ezergy is equal to reduction in enthalpy minus increase in potential energy. Ezergy is a function of the initial conditions (pressure, temperature, and mixing ratio), of the final pressure and of change in elevation. For deep convection, the ezergy (E_z) of air raised to the 15 kPa level is a fair approximation of the *peak ezergy* (E_{zp}). Warm humid surface air has exergy and ezergy. *Ezergy* is more appropriate than *exergy* for atmospheric energy calculations because there is no practical way of producing work from small temperature differences, especially when the Carnot engine would have to be located at the tropopause. For atmospheric problems, *exergy* is overkill.

The following energy balance for the 15 kPa case of Figure 2 shows that ezergy is a small part of the total expansion work. A exit velocity of 10 m/s would reduce the turbine shaft work by 50 J from 2215 J to 2165 J. Kinetic energy and friction losses in a real process reduce turbine shaft work and can be a small part of the ideal turbine work (E_z). There is an increase in the potential energy of the raised air but no increase in the potential energy of the atmosphere because the potential energy is used to compress the descending air shown in the close cycle analysis of section 4.

- Total expansion work (ΔH): 143,731 J
- Potential energy of pure raised air (gz): 138,991 J
- Potential energy of raised water (mgz): 2,525 J
- Total potential energy $(1+m)(gz)$: 141,516 J
- Turbine shaft work (E_z): 2,215 J

To the flow of heat is due all motion including every form of atmospheric motion. Mechanical energy is more valuable than thermal energy. Exergy and ezergy are real work. In ideal reversible processes, mechanical energy can be transformed from one form to another and be transferred from one place to another without loss. Mechanical energy can degrade to heat. In the atmosphere, the fraction of heat that can be converted back to mechanical energy is limited to less than 20 % by the second law of thermodynamics, by Carnot efficiency.

In 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. *The emergy of a gas turbine is simply its ideal work.* In figure 2, the *ezergy* of overall process 1-4 (E_z) is equal to the *emergy of turbine process 1-3* (E_m). The ezergy of upflow process 3-4 is zero, which is akin to Emanuel (2017) statement: "The upward flow above the boundary layer is always neutral to slantwise moist convection". The present conservation of energy calculation technique will be called the ***ezergy approach*** because there is no ezergy change in the upflow process in every case. The *ezergy* is transferred to the preceding constant elevation process where it either leaves the system as shaft work or degrades to heat.

For given inlet and outlet conditions, ezergy is the same 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 have an expanding cone shape making exit velocity negligible. The conduit need not be vertical and can have a gradual slope because horizontal distance does not matter in a frictionless ideal process. The only connection between the atmospheric process and the exergy/ezergy processes is that they operate the same initial and final conditions.

In an ideal process, there must be an isentropic expander or turbine to get the work out of the system. The ezergy is produced by the expanding 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; drawing showing the boundaries of the thermodynamic system are useful but are not essential. *Ezergy is simply the maximum quantity of mechanical energy that can be produced when a fluid is moved from one location to another without heat transfer.*

Actual work, W_a , for an irreversible adiabatic process is less than ezergy because ezergy easily degrades to heat. For the same initial and final conditions, the enthalpy reduction is smaller for an irreversible than for a reversible process. In a fully irreversible process actual work, $W_a = 0$ and $\Delta H = g\Delta z$; 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 less than ezergy (E_z) in irreversible processes or in processes with significant exit kinetic energy.

Ezergy is akin to Convective Available Potential Energy (CAPE). With CAPE, upward acceleration depends on the difference in density between the rising air and the surrounding air; this density difference changes with elevation. With CAPE, the kinetic energy of the air increases as it rises. With *ezergy*, the mechanical energy is produced wherever the flow is restricted. CAPE is based on Newton's laws, on the Archimedes (260 BC) buoyancy principle. *Ezergy* is based on conservation of energy, on the first law thermodynamics, Clausius (1850).

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 is usually smaller than SCAPE. CAPE calculations can be based on actual or virtual air temperature. There are various methods of calculating the expansion temperatures used to calculate CAPE, Holland (1997), and Bechtold (2019). CAPE calculations start at the level of free convection (LFC) and terminate at the level of neutral buoyancy (LNB). Ezergy calculations can start and finish at any elevation; the default is from the earth's surface to the LNB. Ezergy includes CAPE and Convective Inhibition (CIN). CIN is negative and typically between 0 and -100 J/kg. For expansion without separation of condensed water, ezergy is the algebraic sum of CAPE and CIN, E_z = CAPE + CIN. E_z is slightly less than CAPE because CIN is negative.

Ezergy 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 eventually making the environment more favorable for deep convection. Evaporative cooling associated with entrainment reduces buoyancy, Michaud (1998), Bechtold (2019).

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, in an ideal process, there is no friction loss and no heat transfer. 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. Ezergy can produce a velocity (V) of $\sqrt{2E_z}$ throughout the length of the conduit. An ezergy of 2500 J/kg corresponds to a force 5 hurricane velocity of 70 m/s. The kinetic energy can be the exit velocity or can be partly extracted with expanders located anywhere in the conduit. In an adiabatic irreversible process: turbine work, exit kinetic, friction losses in the conduit, and friction losses in the turbine could be 50 %, 10 %, 25 %, and 15 % of E_z respectively.

In a continuous process, the ezergy 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 ezergy approach is far simpler than CAPE. The ezergy approach calculates work directly; the CAPE approach requires integrating the buoyancy area.

The effect of subsidence warming on final elevation is negligible because the downflow takes place far from the upflow 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 change in the level of the final elevation is small compared to that of surface air temperature or humidity.

Ezergy is real work, it can produce shaft work or kinetic energy; it can produce vertical or horizontal velocity; it can increase potential energy; and it can produce electricity which can be transmitted anywhere. Computational fluid dynamics models (CFD) have difficulty arriving at the realization that work of convection can be concentrated and captured at a remote location. CFD calculates the flow, which is very difficult since there are many possible paths. Thermodynamics specifies the flow and calculates the maximum work. Atmospheric efficiency is an oxymoron because, in the atmosphere, 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.

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. Actual energy (W_a) production is difficult to calculate because most of the ezergy degrades back to heat without producing significant kinetic energy. Zipser and LeMone (1980) show that the kinetic energy of strong GATE updraft is typically less than 4 % of CAPE.

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 under -20 °C, at which point the condensed water is all in the ice phase.

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

Ezergy calculations are based on expansion without separation and with freezing of the condensed water. Williams and Renno (1993), WR (1993) hereafter, recommended that CAPE be calculated based on no separation and freezing. Expansion with immediate separation is at time called irreversible or pseudo-adiabatic. In this article irreversible relates to mechanical energy degradation in the thermodynamic sense and not to separation. Molinari (2012) avoided the name pseudo-adiabatic; all three WR (1993) processes are reversible constant entropy processes.

WR(1993) and Molinari (2012) shows that CAPE for expansion with no separation and freezing is almost identical to CAPE for expansion with immediate separation and without freezing. Latent heat of fusion more than offsets the negative-buoyancy contribution due to condensed water loading. WR (1993) state that while it may be unrealistic to carry condensed water to the upper troposphere, it is even more unrealistic to prevent the water from freezing. In addition, the absence of separation keeps the composition constant making eq (2) and steady-state open system techniques applicable. The potential energy of the condensed water is smaller with immediate separation.

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. 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 is Δgz multiplied by $(1 + m) = 1.0182$ 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 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 pure 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 1.82 % of the mass content and 63.7 % of the heat content! The enthalpy of pure air at 15°C is 15,070 J/kg. Taking the temperature base as 15°C, water vapor could contribute 80 % of the upward heat transport. The vapor content must condense to contribute to the upward heat transport; latent heat is only released above the lifting condensation level (LCL). The temperature of rising air decreases by ≈9.8°C/km and by ≈4°C/km below and above the LCL respectively. At lapse rate of 6.5°C/km, rising air loses buoyancy below the LCL and gains buoyancy above the LCL.

Per unit mass calculations permit case comparison. Ezergy is independent of time and velocity. 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.

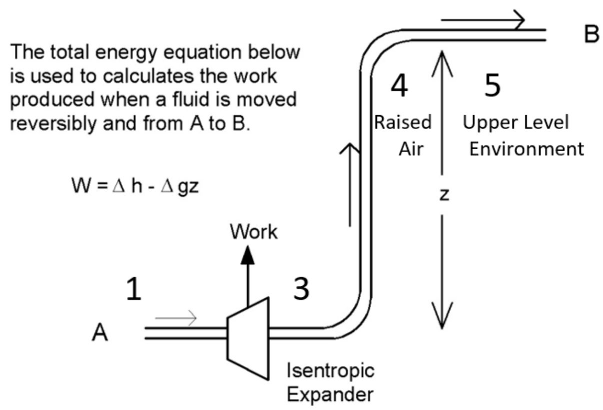
A small tornado with a 30 m base diameter could have an upward flow of 10000 kg/s (10 t/s). At this standard flow, an ezergy of 2215 J/kg correspond to a power output of ≈22 MW. Flow increases with the square of diameter. Power potential is proportional to ezergy and to the square of vortex base diameter. A 300 m diameter tornado could have an upward flow of 1000 t/s and produce ≈2.2 GW 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 of 10 t/s 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. Friction losses in the tuba of a tornado are a small fraction of *ezergy*.

Taking the average convective heat flux at the bottom of the atmosphere averages ≈100 W/m2, Trenberth (2009). The heat received in a 20 km by 20 km is 400 GW(t) and could produce 2 GW(e) in a 300 m diameter-controlled tornado.. Two thousand 300 m diameter-controlled tornadoes located several hundred kilometers apart could produce the current electrical power demand of 4 TW.

3. 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 (IE), the ezergy increment divided by the heat supplied, ranges from 27.2 to 30.5 %. IE is slightly higher for sensible heat addition than for latent heat addition because there is no need to raise additional water.



Basis:
Jordan Caribbean hurricane sounding
P_1 = 101.51 kPa,
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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.

WR (1993) showed that CAPE increases by about 1000 J/kg per degree Celsius increase in surface air wet bulb temperature. They showed that CAPE values in the order of 1000 J/kg are common over large area of tropical oceans. Despite this wide availability of CAPE, deep convection only occurs a relatively small area. The mean convection area is about 7 % of the high CAPE area. They asked: “Why is the convection area such a small fraction of conditionally unstable area?” They suggested that CIN and mixing of dry ambient air in the rising updraft may be inhibiting convection. Michaud (1998) and Bechtold (2019) showed that entrainment of dry ambient air drastically reduces buoyancy.

Converting 30 % of heat received at a temperature of 30°C to work would be a feat for any engine. Conventional thermal engines typically require temperatures differences of at least 300°C. Thermosyphons are an exception and can produce intense circulation from a small temperature difference. Coffee percolators perform work by raising water with a small temperature difference; without the upflow tube the work degrades to heat.

The reason for the ability to produce work from small temperature differences is that a small reduction in density is enough to render a fluid buoyant and to make it rise. 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.

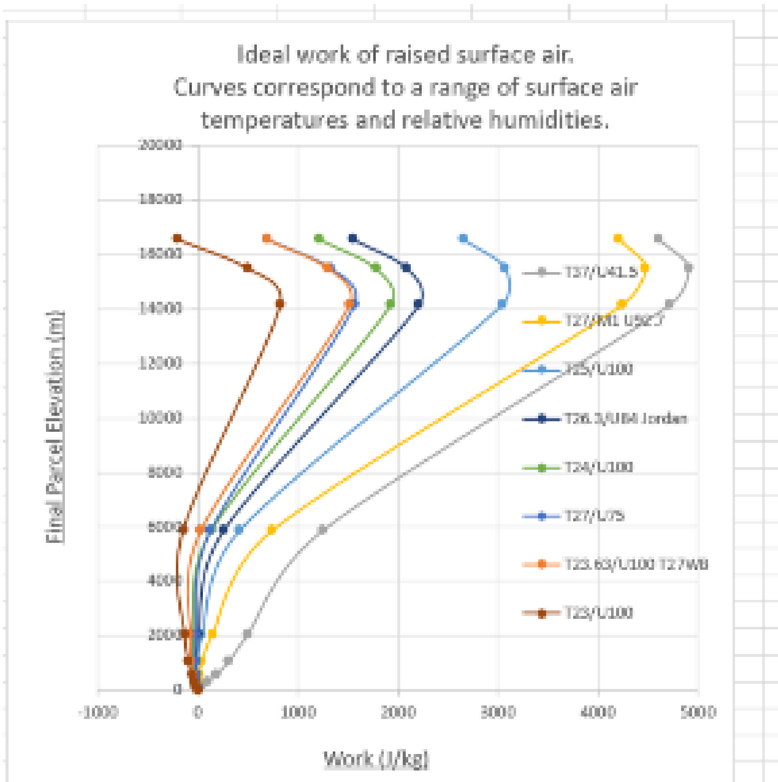


Fig.4 Effect of surface air temperature and humidity on ezergy.
Based on Jordan hurricane-season sounding.

The previous calculations are for a reversible process where the work leaves the system. In a fully irreversible process, dissipated work is greater than the 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 (E_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. The ezergy maximum occurs close to the 15 kPa (14.2 km) level in every case. In the 27°C case reducing the relative humidity from 75 % to 64 % would reduce exergy from 1564 J/kg to zero.

There is a negative ezergy minimum, an *ezergy neap* (E_{zn}), at low level corresponding to CIN. In oceanic tropical areas, CIN and E_{zn} values are usually between 0 and -40 J/kg, WR (1993). Surface air can be in a metastable state and may have to be raised several kilometers to produce significant positive ezergy. For the same wet bulb temperature, dry bulb temperature has negligible effect on ezergy peak and significant effect on ezergy neap. At a wet bulb temperature of 23.6°C, reducing the dry bulb temperature from 27 to 23.6°C reduces ezergy neap (E_{zn}) from -28 to -78 J/kg (by 200 %) and reduces *ezergy peak* (E_{zp}) from 1565 to 1520 J/kg (by 3 %) respectively. For the same wet bulb temperature, reducing dry bulb temperature strengthens the metastable state (E_{xn}) and has negligible effect on Exergy peak (E_{xp}).

Ezergy equation (2) is applicable to any mass of fluid including 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. The ezergy equation is valid for ascending 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, because the work of compression is greater than the decrease in potential energy. CAPE and CIN apply to moving air from one specific position to another. *Ezergy* (E_z) is more generic than CAPE and is applicable to moving air from any place to any other place, usually from the surface to the LNB and includes CIN. CAPE is the work produced when surface air is raised from the level of free convection (LFC) to the level of neutral buoyancy (LNB) and does not include CIN.

Ezergy is transferred downward to overcome resistance to flow wherever it occurs in the conduit, including raising surface air up to the level where it becomes buoyant. A temporary heat source or other disturbance may be required to overcome the metastable state and to start the flow. Starting the upward flow is akin to starting a syphon or a thermosyphon. There is no need for heat input once the circulation has been resulting in very high incremental efficiency.

Fig. 5 shows the effect of initial pressure or elevation on ezergy. Ezergy decreases rapidly with source air level. The ezergy of air initially at the 95 kPa level is about 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. WR (1993) showed that CAPE decreases by 150 to 250 J/kg per 100 m increase of initial elevation. The layer of high ezergy surface air is thin.

Raising high enthalpy surface air is the main atmospheric work production process; this should not be surprising since the atmosphere is heated from below and cooled from above. 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. Cooling of the upper troposphere air by precipitation can produce intense downdrafts but prior updrafts are required to produce the condensed water. In an atmospheric vortex engine, a short tower helps prevent the base of a vortex from drifting away from a vortex engine since the ezergy of ambient air at the top of the stack is less than the ezergy of surface air.

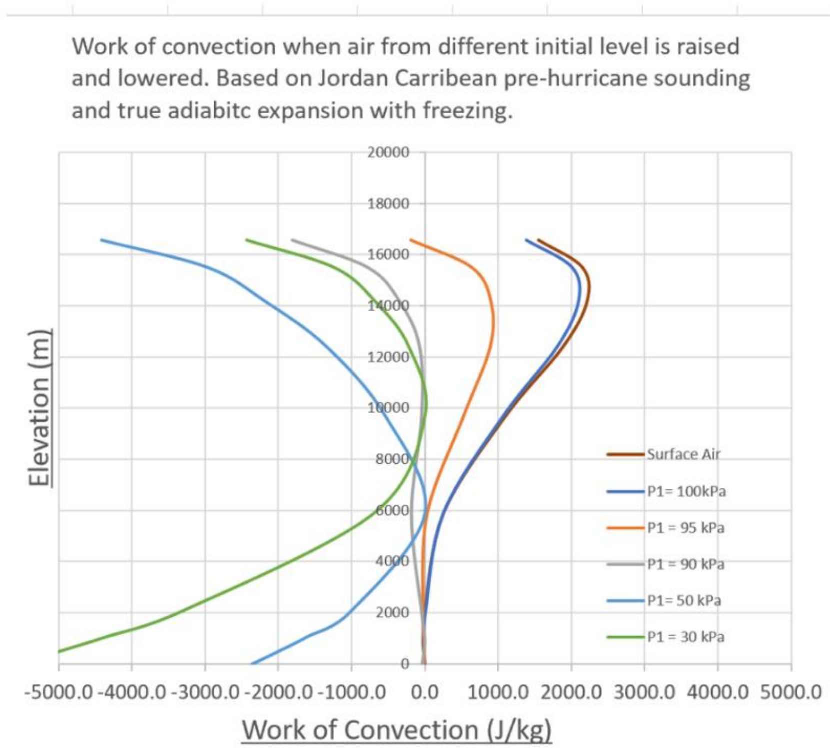


Fig. 5 Effect initial air level of on ezergy.

The ezergy of air initially above the 2 km level 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 in an expanding spiral. Internal kinetic energy can be large without violating conservation of energy provided the kinetic energy is recovered so that the air leaves the system at low exit velocity. The high internal velocity provides centrifugal force and prevents the higher external pressure from driving the ambient air into the lower pressure air rising in the high velocity vortex annulus thereby suppressing mixing, turbulence, and frictional losses.

In a vortex, ezergy production takes place in an annulus of rising air near the radius of maximum tangential wind. The work is produced by the expansion of the air rising in the annulus. Ezergy equation (2) applies to the air in the rising 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. The intensity of the vortex is partly attributable to centrifugal force in the annulus preventing the rising air from being diluted by surrounding ambient air. The initial rotation is not the energy source. Conservation of angular momentum requires that the tangential velocity increase as the air converges into the vortex base. Surface friction reduces angular momentum and centrifugal force permitting convergence in the thin surface layer.

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 core plays no role in energy production. The effect is the same as if some of the work produced by the turbine were used to drive a vertical axis pump impeller located in the base of an open bottom chimney. Pulling down air from the troposphere would require ≈11000 J/kg, forced core rotation can not produce more than ≈5000 J/kg. 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 on the axis of the vortex. 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 rising annulus.

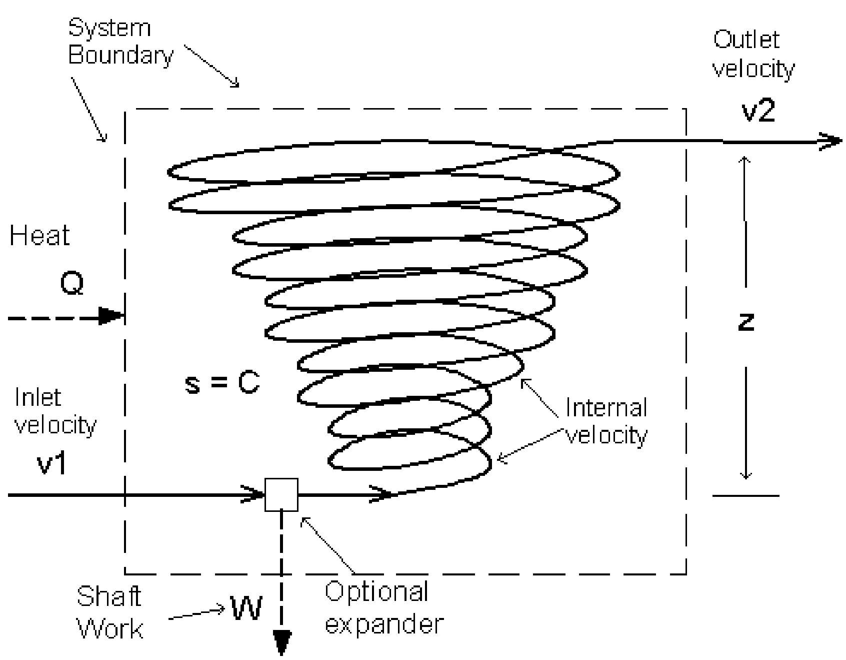


Figure 6. Continuous flow system with a spiral path. High internal velocities do not affect the energy balance which only depends on external energy flows.

Margules (1903) used closed thermodynamic systems and showed that available energy is equal to reduction in total system enthalpy. Open thermodynamic systems were not widely used before Heike Onnes coined the name enthalpy in 1909. 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 the minimum total enthalpy that could be achieved by rearranging the mass via reversible adiabatic processes. The Lorenz 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 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. The atmosphere never comes close to the reference state. There have been numerous articles expanding on the reference state concept.

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)	Updraft Base Pressure P_3 (kPa)	Central 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.
* Final pressure and elevation 10 kPa and 16577 m case.
** based on updraft to center ΔP 30 % of overall ΔP.

Initial Surface Air Conditions			Work Potential – Irreversible			
Temperature T_1 (°C)	Mixing Ratio M_1 (g-w/kg-air)	Relative Humidity U_1 (%)	Inergy E, (J/kg)	Potential Velocity (m/s)	Updraft base Pressure P_3 (kPa)	Central 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.
* Final pressure and elevation 10 kPa and 16577 m case.
** based on updraft to center ΔP 30 % of overall ΔP.

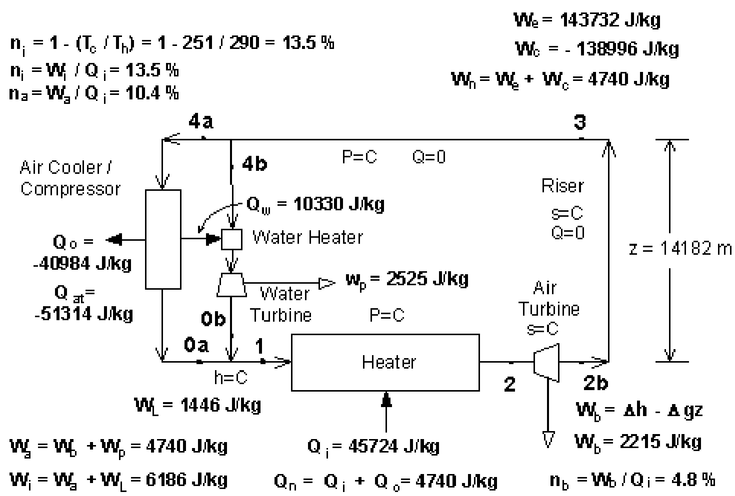
Tables 1a and 1b show the effect of surface air temperature and humidity on exergy and potential velocity for reversible and irreversible ascent. Potential velocities of greater than 130 m/s can be produced by raising 45 °C and 35 °C air in the reversible and irreversible cases respectively. Surface 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 transferred from dust to air can increase air temperature.
Bister and Emanuel (1998) showed that Irreversibility 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 and 2 of Table 1a by 3,1 °C, 3033 J/kg.

Several authors 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, if the subsidence is local, the available energy is too small to explain observed tornado energy. Low potential velocity may be partly due to the fact standard CAPE is based on raising air with the average properties of the bottom 500 m. The CAPE of air from the 0.2 m level can be 2 to 4 times standard CAPE.

Supercells and thunder clouds are not the energy source for tornadoes; thunder clouds are the result of updraft of warm humid air. Expanding surface air from 101 to 15 kPa can produce 145,000 J/kg but the air must be raised 14 km requiring 140,000 J/kg. The difference, the ezergy, is the only part of the work of expansion available to produce shaft work.

4A. Close cycle

Close reversible cycles, widely used to calculate the efficiency of thermal engines, have rarely been applied to the atmosphere, Michaud (2000). Efficiency cannot be calculated for the open process of Fig. 2 and 3 because the cycle is incomplete; there is no heat input. Engine efficiency calculations require closed cycles wherein the same working fluid goes thru a complete close cycle such as shown in Figure 7.



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 conditions in process 2-3 of the close cycle of 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.
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 the real atmosphere, where the moisture can be provided by mixing of ambient air with shallow updrafts, the work loss (W_L) could be smaller. In the ideal

cycle of figure 7, heating process 1-2 is reversible; the air and the water are in equilibrium; the heat source is at a temperature just slightly higher than the temperature of the saturated air water mixture. In the real atmosphere where the heat source is significantly warmer than the air, the heating process is irreversible. The cycle of Figure 7 is not identical to the atmospheric process; the cycle is analysed to arrive at thermodynamic understandings applicable to the atmosphere.

"*Overall Work*" (6186 J/kg) is defined as 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 the heat received 13.5 % (=6186/45724). Overall Efficiency is also equal 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. In the ideal cycle, the work of the air and water-turbines leave the system. The work of the air-turbine could be used to produce valuable mechanical energy.

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. In the real atmosphere, the re-humidification water need not be the water that ascended and can come from the sea via shallow updrafts. Unsaturated air has high affinity for water. As a result, oceanic surface air typically has relative humidity of ≈ 80%, WR(1993) and Holland (1997),

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 84, 69.7 and 0 % relative humidity are 2215, 0, and -12353 J/kg respectively. The corresponding surface air enthalpies are 72800, 64900 and 26400 J/kg. Surface air enthalpy of ≈64900 J/kg can be viewed as the *enthalpy-zero.* The 38500 J/kg received under the enthalpy zero is insufficient to make ezergy positive. The ezergy is 4.8 % (2215/45724) of the total heat received and 28 % (2215/7900) of the heat received above the *enthalpy-zero*. WR(1993) used the name *wet-bulb potential temperature intercept,* a concept akin to *enthalpy-zero*.

Adding a small amount of heat can releases the potential of heat received from prior natural heating. Tropical ocean surface air ezergy is usually around 1500 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 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 is approximately 25 %.

The close cycle of Fig. 7 can explain many features of the atmosphere. The ezergy is 4.8% (2215/45724) of the total heat received. The total turbine work is 10.4 % (4740/45724) of the heat received. 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 in CAPE analysis. 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. For a fully irreversible cycle, total actual work (W_a) is zero and heat out (Q_o) equals heat in (Q_i).

In the closed cycle of Figure 7, conservation of mass requires the upward and downward mass flow be equal. In the real atmosphere, subsidence occurs preferentially where the air is coolest and densest. Local subsidence would increase the local temperature and the local 15 kPa elevation which would push the subsidence area away from the upflow area. Local subsidence compresses and warms underlying air thereby favoring remote subsidence. The subsidence process is self-regulating; the subsidence takes place preferentially where the subsiding air is coldest and needs warming.

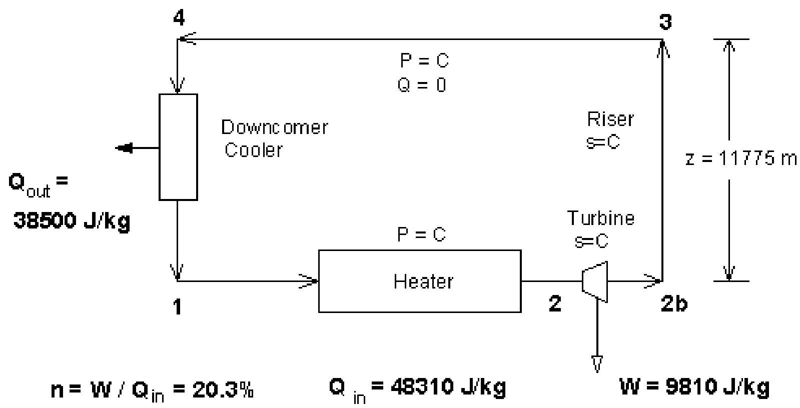
There is no change in potential energy in a steady-state closed cycle. Work not captured by the turbines becomes work of compression. Energy is transported poleward mainly by work of compression rather than by sensible or latent heat. The descending air received 138986 J/kg as work of compression which provides its increase in enthalpy of 87662 J/kg plus its heat loss of 51314 J/kg. 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 choices of polytropic cooling for the descent and adiabatic isentropic for the ascent. Goody (2003) describes a close cycle similar to Figure 7; he recognised that downward velocity has to be much slower than the upward velocity to give the subsiding air time to cool; he recognised that the only irreversible process in the close cycle is the mixing and heating near the earth's surface.

Raising 1 kg of surface tropical air can transfer 140,000 J of energy upward and poleward. Transferring 140,000 J of energy poleward by heat transfer would require cooling 28 kg of air by 5 °C, 28 times more air mass than by compression. The role of work of compression in transporting energy poleward is seldom recognised. The enthalpy of a column of air can be increased by adding air at the top of the column while removing the same quantity of air from the bottom because static energy increases with elevation.

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 (6mm/s). 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 wander; the corresponding subsidence occurs preferentially where the air is coldest. Additional information can be found at Michaud (1998, 2000 and 2012).

The mixing of all the condensed water with the cooled air of Figure 7 may not be realistic. Adding the water gradually while adding heat to prevent the temperature from falling would result in similar efficiency. Warm water spray can have an equivalent effect; a small part of the spray evaporates while the rest cools providing sensible heat.



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

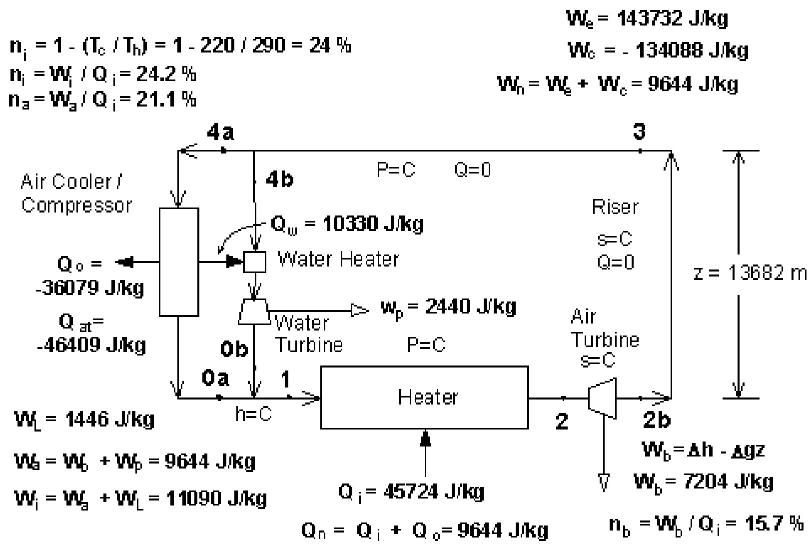
$$n_c = 1 - T_c / T_h = 1 - 248.8 / 313.1 = 20.5\%$$

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 and can be perfectly reversible. Figure 8 shows a pure air single component fully reversible cycle. Height is based on a lapse rate is 6.5°C/km. The raised air is at the temperature of the environment in state 3. The initial temperature of the rising air is 55°C which would be very unstable. The net work is transferred to the turbine where the flow is restricted.

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 height 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 name ***epergy*** will be used for exergy based on the use of an upper-level elevation lower than the local upper elevation. The "*p*" stands for poleward. Raising air in high latitude can increase energy production. *Exergy* is free, *ezergy* is freer, and *epergy* is freer yet.



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..

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

According to Kleidon (2022), the maximum heat to work conversion efficiency of the atmosphere based on the temperatures at which heat is received and given up is ≈ 10 % in accord with present Figure 7. According to Kleidon (2021), the maximum wind energy production is 0.2 % of absorbed solar energy of 240 W/m^2, resulting in a global mean estimate for the wind energy potential of about 0.5 W/m^2. According to the ezergy approach, the maximum energy production is 10 % of the upward heat flux of 100 W/m^2 resulting in a global mean estimate energy production of ≈ 10 W/m^2. Kleidon's wind energy potential is based on horizontal temperature gradient, on horizontal heat flux, and on Betz turbine efficiency limit. Kleidon's wind energy potential is 50 times smaller than his potential based the temperatures at which the atmosphere receives and gives up heat. Figure 2 shows that upward heat convection can produce horizontal wind at remote location. Kleidon (2011) did not consider the contribution of upward heat flux to horizontal wind.

The fact that polar energy transfer is mainly via work of compression has seldom been recognised. The winter pole looses ≈ 150 W/m^2 by radiation to space, Kleidon (2021); its temperature is roughly constant throughout the winter. There must be an energy source to make up for this heat loss. Work of compression must be this energy source.

Over a century ago in his last paper, which received little attention, Margules (1906), wrote:

1. I hold vertical movement under the influence of gravity to be the essential cause of storms.
2. 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.
3. One could gain a closer understanding, when better method than presently known, for the handling of aerodynamic problems are found.

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, Holland (1997).

The open process of Figure 2 and the close cycle of Figure 7 provides independent validation of mechanical energy production. Esergy is equal to reduction in moist static energy (2); overall work is equal to heat input times Carnot efficiency based on the average temperatures at which heat is received and given up (4).

The cycle need not be continuous as shown in Figure 7; it can consist of three stages: heating, convection, and cooling. Heating must take place before convection. Convection produces the work and while immediately warming the descending air by compression. The cooling of the descending air by radiation to space can take place long after the convection. The heating can take place long before the convection. The heat received and given up during the convection process is a negligible part of the heat carried upward. The heat stored in tropical seas in the summer can power hurricanes in the fall.

4B. Seamless poleward and upward atmospheric energy transport.

In Figure 7, the emergy, the work of expansion from P2 to P4, of 143,732 J/kg is enormous compared to the ezergy of 2,215 J/kg. The ezergy is much smaller than the emergy because 141,517 J/kg is required to raise the air and its water content. The emergy and ezergy correspond to velocities 516 and 65 m/s respectively. The velocity of sound in air is about 340 m/s.

The troposphere is heated from the bottom by solar radiation and cooled from above by infrared radiation to space, but the subsiding troposphere is heated by compression. Expansion produces work; compression requires work. Figure 5 shows that raising air from the lower atmosphere air is essentially the only work production process. Raising or lowering air from the upper troposphere air requires work.

The driver for atmospheric upward heat convection is the heat content of surface air. Subsidence can not occur unless some of the surface air rises and makes room for the descending air. Upward flow controls both the upward and downward flow. Conservation of mass requires that downward flow equal upward flow. Subsidence tends to take place where the underlying air is cooler and easiest to compress; surface air is pushed from the subsidence area towards the updraft area wherever it may be. The metastable state of surface air makes it possible for a small heat addition to produce updrafts.

Work of expansion of rising air is real work. Compressing subsiding air requires real work. In reversible processes, work can be transformed from one form to another. Most of the work of expansion of the rising air goes to increasing its potential energy. The work of compression of the descending air comes from the potential energy of the overlying air. Subsidence diminishes the potential energy of the overlying air. Upward convection restores the potential energy of the overlying air. The overlying air is a reservoir of potential energy awaiting an opportunity to compress and push down the underlying air. Most of the work of expansion of ascending air is unavailable to produce shaft work because it is required to compress descending air. The overlying air mass is a reservoir of potential energy where work of expansion is stored and made available as work of compression thereby transforming work of expansion to work of compression.

Atmospheric upward heat convection consists of small fast updraft areas and of large slowly subsiding areas more than to Hadley and Ferrel circulation cell of roughly equal upflow and downflow areas. Heavy precipitation areas and strong updraft areas typically cover less than 1 % of the earth surface.

The troposphere is cooled by about 1.5 °C/d by infrared radiation to space. At a subsidence velocity of zero, 0 m/d, the temperatures at a given level would decrease by 1.5 °C/d. At a subsidence velocity of about 500 m/d the temperature at a given level is constant. At a subsidence velocity of about 1000 m/s mid troposphere temperature would increase by 1.5 °C/d. Several updrafts can contribute to the same subsidence area. The contribution of subsidence to poleward energy transport is seamless because reduced mid troposphere temperature increases local subsidence. Subsidence warming can take place in cloud free tropical areas as well as in high latitudes.

Trenberth and Stepaniak (2003A and B) asked how come poleward energy transport is so seamless? Why does atmospheric energy transport increase when oceanic energy transport decrease? Cox et. al. (2022) asked how come mountain range have little effect on total poleward energy transport. Atmospheric models were used in both studies. There is a simple explanation, subsidence velocity increases when mid troposphere temperature decreases. The process is self regulating.

Carnot (1825) proposed a simple close cycle to explain mechanical energy production in thermal engines. His approach is applicable to all thermal engines. He wrote: " to the flow of heat is due all movement including wind and precipitation". Atmospheric models have difficulty explaining poleward energy transport. Ideal thermodynamic cycles correctly explain the maximum efficiency of all thermodynamic engine. Michaud (2000) proposed using close gravity cycles wherein the air is cooled while it subsides. Process engineers have experience with power cycles which could be valuable in atmospheric science.

The gravity cycle explains how the inversion at the top of the boundary layer inhibit upward heat convection thereby enhancing the metastable state. High moisture in the lower troposphere could reduce radiative cooling rate from about 1.5 to 0.5 °C/d. At a subsidence of 500 m/s, the temperature could be constant at the 10 km level and could increase by 1 °C/d at the 1 km level.

Atmospheric models recognise that Moist Static Energy (MSE) transfers energy poleward. MSE has a heat part and a potential energy part. Potential energy is more valuable than heat. Heat can not provide work of compression. Lumping heat and work together in MSE hides the fact that the poleward energy transfer is due to the potential energy of the overlying air. The temperature of the overlying air does not matter, the temperature of the subsiding air increases irrespective of the temperature of the overlying air.

5. Sea water spray – Tropical cyclones and waterspouts.

Mechanical energy production can be increased by spraying the air with sea water. Figures 10 and 11 and Table 2a, 2b, and 2c show the effect of spraying air with sea water. Spraying ambient air, to produce 25°C 90% relative humidity air can increase ezergy from 1564 to 2983 J/kg, corresponding to velocities of 55 and 76 m/s. Available work with sea spray will be called ***esergy*** *(E_s)*, where "*s*" stands for "Spray*".*

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

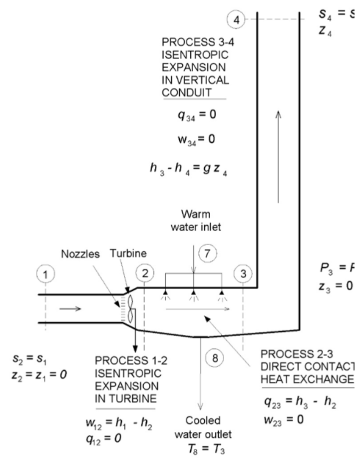
True adiabatic with ice.

$W_b = W_{12}$ = 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)

The relative humidity of air at equilibrium with fine water droplets must be 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, Andreas, and Emanuel (2001), Sroka and Emanuel (2021). The relative humidity of surface eyewall air can be slightly less than 100% due to mixing of saturated air with air that received less spray. Hurricane eyewall air is always close to saturation. Montgomery (2005) reported eyewall temperature and humidity of 24°C and 98% in category 5 hurricane Isabel. *P_3* can be calculated with a solver and is simply the pressure for which the ezergy of process 3-4 is zero.

Saturated air of any temperature up to the spray temperature can be produced by increasing the quantity of spray; the quantity of spray required increases exponentially with temperature.

At high spray-to-air mass flow ratio, the temperature of the saturated air approaches the temperature of the sea water.

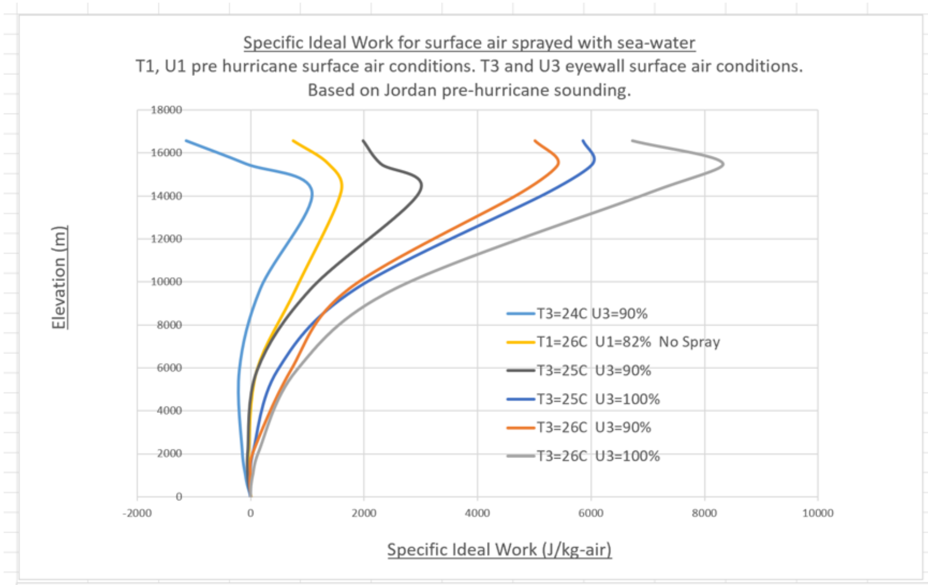


Figure 11. Effect of water spray on ideal work (Evergy). Curves show effect of eyewall temperature and relative humidity.

A small fraction of the spray evaporates, typically 0.5 %; the remaining 99.5 % falls back into the sea. The heat of evaporation is provided by the part of the spray which does not evaporate, and which falls back in the sea at the wet bulb temperature of the air. The enthalpy transfer process is an equilibrium process and rather than a water surface to air enthalpy transfer process. The first few grams of spray evaporate completely; the latent heat of evaporation is initially supplied by the air thereby reducing the air temperature to its wet bulb. A spray of 400 grams of water spray per kilogram of air can produce 25°C saturated air. Increasing the temperature of the saturated air requires more spray when the initial temperature or humidity of the air is low and less spray when the spray temperature is higher. *Esergy* is not completely free, the air must be sprayed with warm water to increase it heat content; warm sea water is free.

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_S Esergy (J/kg)	Velo-city (m/s)	P_3 (kPa)	P_C (kPa) ΔP_e = 1.43 ΔP_3	P_C (kPa) Holland Fig. 13	F_7/F_3 g-w / kg-a
Without sea water spray									
N/A	27	75	16.95	1560	55	99.7	99.0		0
Section 1: $T_7 - T_3$ = 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	530
27	26	90	20.3	4790	96	96.1	93.8	95	1230
28	27	90	22.0	6500	112	94.2	91.1	92	1940
Section 2: 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		280
28	26	90	20.3	4790	96	96.1	93.8		860
28	27	90	22.0	6500	112	94.2	91.1		1940
Section 3: T_3 = 25 °C U_3 = 90 %									
24	25	90	18.6	2980	76	98.1	96.7		4780
25	25	90	18.6	2980	76	98.1	96.7		960
Section 4: T_7 = 28 °C U_3 = 100 %									
28	23.5	100	18.8	2480	69	98.7	97.5		175
28	24	100	19.6	3430	81	97.6	96.0		400
28	25	100	21.3	5260	100	95.6	93.1		1090
28	26	100	23.1	6980	116	93.7	90.4		2500

Table 2a. Effect of sea water spray on esergy. 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 kPa/K, versus 2.6 and 3.3 kPa/K from Holland Figure 13 and Table 5 respectively, versus Emanuel 1.05 kPa/K (Holland Table 2).
Sensitivity of central pressure to updraft relative humidity: 0.36 kPa/%, versus Holland 0.48 kPa/%, versus Emanuel 0.62 kPa/%.

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 sea surface. The affinity of water to air is zero for water at the dew point temperature of the air and increases rapidly with water temperature.

Several indices of hurricane maximum potential intensity (MPI) have been used. E-MPI, Emanuel (1987), used maximum velocity. H-MPI, Holland (1997), used minimum central surface pressure. Esergy is more appropriate than maximum wind velocity or axial pressure because it is based on energy conservation. The central pressure is unimportant in energy calculations because the eye plays no role in the energy production. The ezergy approach yields ideal work, velocity, and the pressure at the base of the updraft, but not the central pressure. The central pressure reduction can be 1.4 to 2 times the pressure reduction at the rising air annulus (T_3). According to Willoughby (1998), hurricane eyewall to the center pressure reduction is approximately 30 % of the overall pressure reduction which corresponds to a factor of 1.43. In Table 2a, the central pressure (P_c) reduction is taken as 1.43 times the base of the updraft pressure reduction (P_1 - P_3).

In the 26°C 90 % relative humidity case, the mixing ratio increases from 16.95 to 20.25 g/kg, by 19 %; the work increases by a factor of 3 from 1564 to 4790 J/kg. The work of expansion is transferred from process 3-4 to process 1-2. The ideal work is transferred to the turbine where the flow is restricted. E*mergy* 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.

Rising air conditions are important because the work of expansion is produced during the upflow is used to raise the air and to drive the turbine. Sea-surface temperature at the eyewall can be 1 to 2°C lower than pre-hurricane sea surface temperature. Holland (1997) recommended using updraft temperature 1°C colder than pre-hurricane SST and an updraft relative humidity of 90 % because the condensation level in hurricanes is typically around 500 m. Table 2a shows that Holland's recommendations are appropriate. Minimum axial pressures P_a and sensitivity to T_3 agree with Holland (1997) figure 13.

The Holland and esergy methods are compatible. Holland calculates eye pressure from hydrostatics. The *esergy* approach calculates annular updraft base pressure from energy conservation. In both cases the air is brought to equilibrium with the sea water. Holland uses isentropic expansion with immediate separation and no freezing. The present calculations are based on isentropic expansion without separation and with freezing of condensed water. WR(1993) showed that CAPE is almost identical for these two types of expansion.

Sea surface temperature and the quantity of spray are by far the dominant environmental contributors to hurricane intensity. The effect of the elevation of the level of neutral buoyancy is minor compared to the effects of sea surface temperature or of pre-hurricane surface air temperature and humidity. Without spray, the quantity of high *ezergy* ambient surface air is small because the high humidity layer is thin. Spray can produce large quantities of high humidity air because the heat content of the ocean is far greater than that of the thin surface air layer.

Pre-storm surface air can have *ezergy* of 3000 J/kg able to produce force 5 hurricane wind of 77 m/s. Spray can increase *esergy* to 5000 J/kg corresponding to wind of 100 m/s. Hurricane intensity may be more attributable to quantity of air than to its specific esergy. Spray increases both air esergy and air flow. Increasing air flow limits esergy to around 5000 J/kg.

In per unit mass simulation, the air flow is constant making it easy to see that the *esergy* intensity increase with spray flow. Spray at SST is effective at producing esergy, spray that has been cooled to the wet bulb temperature of the air is no longer effective. Large drops and globs such as breaking wave crests are less effective than small drops of the same mass. In the ideal process of figure 10, the spray is injected at a single point. In a hurricane spray increases with decreasing radius. Spray injection radius has little effect on spray effect. Actual spray-to-air ratio would be difficult to measure. Therefore spray-to-air ratio can mean a gradually increasing flow equivalent to a single point eyewall injection. Spray to air flow ratio is seldom considered by atmospheric models.

Sea Surf. Temp SST	Conditions at Updraft Base			Potential Intensity					Spray to Air Mass Flow Ratio
T_7 (°C)	T_3 (°C)	T7 – T3 (°C)	U_3 (%)	M_3 Mixing Ratio g-w / kg- air	E_S Esergy (J/kg)	Velo-city (m/s)	P_3 (kPa)	P_C (kPa) ΔP_e = 1.8 * ΔP_3	F_7/F_3 g-s / kg-a
Without sea water spray									
N/A	27	N/A	75	16.95	1560	55	99.7	98.3	0
Section 1: $T_3 = 24 + (T_7-27)/4$									
23	23	0.0	98	17.53	1050	45	100.31	99.36	N/A
25	23.5	1.5	98	18.29	2020	62	99.21	97.37	N/A
27	**24.0**	**3.0**	**98**	**19.08**	**2980**	**76**	**98.13**	**95.43**	**375**
29	24.5	4.5	98	19.90	3910	87	97.09	93.56	429
31	25.0	6.0	98	20.75	4820	96	96.08	91.74	459
33	25.5	7.5	98	21.62	5710	105	95.11	90.00	479
35	26.0	9.0	98	22.52	6570	112	94.18	86.84	493
Section 2: T_7 = 27 °C									
27	**24.0**	**3**	**98**	**19.08**	**2980**	**76**	**98.13**	**95.43**	**375**
27	25.0	2	98	20.75	4820	96	96.08	91.74	1280
27	26.0	1	98	22.52	6570	112	94.18	88.31	3650

Table 2b. Effect of sea water spray on esergy. . 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, z_4 = 14182 mg . Symbols are defined In Figure 10.

Section 1 of table 2a shows that producing saturated air 1°C colder than sea surface temperature requires water to air mass flow ratios of 530 to 1940 g-w/kg-air. The flow ratio increases with temperature. Section 2 shows that for a fixed water temperature of 28°C, the mass ratio increases exponentially from 280 to 1940 g-w/kg-air. Section 3 shows that 90 % relative humidity air can be produced by spray colder than the air. Section 4 shows that for a water temperature of 28°C, producing 100% relative humidity saturated air requires a higher spray-to-air mass ratio than producing 90% relative humidity air.

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 its esergy increase with water flow. The effect of spray is cumulative. In the 28 °C SST 100 % relative humidity section 4 of table 2a, increasing the saturated air temperature from 25 to 26 °C requires an additional water flow of 1410 g-w/kg-a (2500 – 1090). 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.

Table 2b shows the effect of sea-water temperature (T_7) and of water-to-air mass flow ratio (F_7/F_3) on updraft temperature (T_3) and on specific work (E_s). The 27°C SST case is based on hurricane Isabel observed conditions, Montgomery (2005). Section 1 shows that the flow ratio is constant of roughly 400 g-w/kg-air when the increase in updraft temperature is a quarter of the increase in SST. There is a slight increase in flow ratio from 375 to 459 g-w/kg-air. Section 2 shows that 27°C SST can produce 26°C, 98% relative humidity air; but the flow ratio increases exponentially by a factor of 10 from 375 to 3650 g-w/kg-air.

The flow ratio is unlikely to be higher than 500 g-w/kg-a because increasing hurricane intensity increases both spray and air flows, thereby limiting the flow ratio. Updraft temperature is unlikely to be over 25°C which is more than sufficient to account for observed maximum hurricane wind velocities. The specific ezergy of updrafts could be higher in atmospheric vortex engines than in hurricane because the air flow can be restricted, as the spray flow is increased.

Maximum hurricane velocity based esergy (5), using actual eyewall SST and a spray ratio of 400 g-w/kg-air could be as accurate as E-MPI and H-MPI. Initial default values could be based on E_x = 1500 J/kg, P_4 = 15 kPa, and z_4 = 14200 m. The effect of pre-hurricane surface air properties, equilibrium level and pressure are minor, but could be considered.

Section 2 of Table 2b shows that updrafts with temperatures 23°C and 24°C and a relative humidity 98% can produce category 1 and category 5 hurricane minimum wind speeds of 33 and 70 m/s respectively.

Spray is an equilibrium process. Surface to air energy transfer calculations are inappropriate for spray. Heat transfer by spray is at least an order of magnitude larger than by sea-surface to air heat transfer. The area of cooling ponds must be at least 1000 times the area of a cooling tower of the same capacity.

Hurricane maximum wind velocity (*V*) is simply:

$$V^2 = 2\,E_s \qquad (5a)$$

Table 2c. Shows the effect of ambient air temperature and relative humidity and of sea surface temperature on eyewall pressure (P_3) and on *esergy* (E_S).

Eyewall pressure P_3 is calculated based on:

- T_3, Eyewall air temperature,
- U_3, *E*yewall humidity,
- P_1, T_1, and U_1, Pre-hurricane surface air, or downdraft air conditions,
- Z_4, Elevation of 15 kPa pressure level, or the actual elevation and pressure of the level of neutral buoyancy (LNB),

Solvers are used extensively to obtain calculated results. P_3 is the pressure for which the *ezergy* during process 3-4 is zero. Esergy (E_S) is the work produced by expanding surface air isentropically from P_1 to P_3. T_4 is based on isentropic expansion of surface air from P_1 to P_4.

Water spray F_7 is calculated based on:

- T_7, Eyewall SST, or pre-hurricane SST minus 1 or 2°C,
- T_2, is based on isentropic expansion of surface air from P_1 to P_3.
- The mixing process is isenthalpic,
- Maximum hurricane intensity could be based on spray-to-air flow ratio of 400 or 500 g-w/kg-a.

For each set of three eyewall temperature and relative humidity, in Table 2c, there is one corresponding set of eyewall pressure and *esergy*. Esergy and eyewall pressure are back calculated from eyewall temperature and relative humidity. Eyewall relative humidity U_3 is adjusted by trial and error to produce the same eyewall pressure in each set of three. Central eye pressure reduction can be 1.4 to 2.0 times the eyewall pressure reduction. Conservation of energy can give every unit mass of flowing air a velocity of V. *Esergy* can be transformed into other forms of energy such as shaft work or leave the system as exit velocity.

T3	U3	P2=P3	T2	U2	M1=M2	M3	H3	H2	Q23	Es	Vs	Es - Ez	ES/Q23	(Es-Ez)/Q23	F7
(°C)	(%)	(kPa)	(°C)	(%)	(g-w/kg-a)	(g-W/kg-a)	(J/kg-a)	(J/kg-a)	(J/kg-a)	(J/kg-a)	((m/s)	(J/kg-a)	(%)	(%)	(g-w/kg-a)
Sestion #1 -- P1 = 101.51 kPa, **T1 = 27°C, U1 = 75%**, M1 = 16.95 g-w/kg-a, P4 = 15 kPa, Z4 = 14182 m, **T7 = 28°C**.															
24	98.00	98.13	24.12	86.38	16.95	19.08	72682	67381	5391	2980	77.2	1417	56.2	26.7	286.42
25	90.00	98.13	24.12	86.39	16.95	18.64	72596	67378	5218	2983	77.2	1418	57.2	27.2	283.48
26	82.60	98.13	24.12	86.39	16.95	18.19	72486	67380	5106	2981	77.2	1417	58.4	27.8	278.68
Sextion #2 -- P1 = 101.51 kPa, **T1 = 27°C, U1 = 75%**, M1 = 16.95 g-w/kg-a, P4 = 15 kPa, Z4 = 14182 m, **T7 = 28°C**.															
25	95.00	96.83	23.00	91.40	16.95	19.95	75932	66208	9724	4153	91.1	2589	42.7	26.6	621.06
26	87.26	96.84	23.00	91.34	16.95	19.46	75778	66222	9557	4139	89.2	2575	43.3	27.0	609.19
27	80.20	96.83	23.00	91.38	16,95	19.03	75677	66213	9464	4148	91.1	2584	43.8	27.3	603.69
Section #3 -- P1 = 101.51 kPa, T1 = 27°C, **U1 = 80%,** M1 = 18.08 g-w/kg-a, P4 = 15 kPa, Z4 = 14182 m, **T7 = 28°C.**															
25	95.00	96.83	22.99	97.49	18.08	19.95	75932	69083	6849	4161	91.2	1812	60.8	26.5	439.08
26	87.26	96.84	23.01	97.42	18.08	19.48	75778	69097	6682	4147	91.1	1799	62.1	26.9	428.38
27	80.20	96.83	23.00	97.46	18.08	19.03	75677	69008	6589	4155	91.2	1807	63.1	27.4	423.62
Section #4 --P1 = 101.51 kPa, T1 = 27°C, **U1 = 75%,** M1 = 16.95 g-w/kg-a, P4 = 15 kPa, Z4 = 14182 m, **T7 = 30°C.**															
25	95.00	96.83	23.00	91.40	16.95	19.95	75932	66208	9724	4153	91.1	2589	42.7	26.6	400.00
26	87.26	96.84	23.00	91.34	16.95	19.48	75778	66222	9557	4139	89.2	2575	43.3	27.0	393.27
27	80.20	96.83	23.00	91.38	16,95	19.03	75677	66213	9464	4148	91.1	2584	43.8	27.3	390.00

Table 2c. Increasing ambient air temperature or sea surface temperature reduces the quantity of spray required to reduce eyewall pressure P_3 and to increase esergy (E_s).

Section #1 shows that different combinations of T_3 and U_3 can produce the same P_3 and E_S.
Section #2 shows that decreasing P_3 or increasing E_S requires increasing spray flow F_7.
Section #3 shows that increasing ambient air relative humidity U_3 decreases spray flow F_7.
Section #4 shows that increasing SST T_7 decreases spray flow F_7.

The ezergy method gets the physics right. Ezergy establishes a clear distinction between mechanical energy produced from pre-hurricane air and the mechanical energy produced from spray. For the 24 °C 98% RH case in Table 2c, E_Z and E_S are 2980 and 1564 J/kg respectively. The heat received from the spray is 5301 J/kg. E_Z is 56% of the heat received. The work increment (2980-1564=1416) is 27% of the heat received. The incremental efficiency is between 25 and 30% for every case of Tables 2c, in accord with the close cycle analysis. Efficiency based on hot and cold source temperatures only applies to heat received. The *esergy* to heat received can be greater than 30% because spray can trigger the release of ezergy production from pre-hurricane air. In the limiting case, where a heat initiates a vortex which persist after the heat source is turned off, the *esergy* to heat input can exceed 100%.

The widely used E_MPI equation, Emanuel (2018), maximum hurricane wind speed equation is:

$$V^2 = \frac{C_k}{C_d}\frac{T_s - T_o}{T_o}(k_s - k_a) \qquad (5b)$$

where V is the maximum wind speed, C_k and C_d are enthalpy and drag coefficients, T_s and T_o are the absolute temperatures of the sea surface and storm top, and k_s and k_a are the enthalpies of eyewall air saturated at SST and air of eyewall boundary layer air. Finding the value of the enthalpy and drag coefficients has occupied numerous researchers for over 50 years, Black et.

al. (2007). The coefficients are a function of velocity and not well known; estimates of the C_k/C_d ratio in hurricanes wind range from 0.3 to 1, Montgomery et al. (2006).

Tropical cyclones are driven by surface enthalpy fluxes. Eq. (5a) is far simpler than Eq. (5b). There is no need for enthalpy difference, or enthalpy and drag coefficients, or Carnot efficiency. The eyewall energy transfer is not between two air mass; it is between an air mass and water mainly in the form of spray. The contribution of the initial mixing ratio of ambient is not considered in E-MPI. Sroka and Emanuel (2021) pointed out that sea-to-air energy transfer is well approximated by using spray flux alone and that drop radius is not important.

The Table 2c 25°C case shows that increasing the eyewall relative humidity from 90 to 95% increases velocity from 77.2 to 91.1 m/s. Eq. (5b) with a C_k/C_d ratio of 0.3 and 1 yields a decrease in velocity from 74 to 68 m/s and from 41 to 37 m/s respectively. E-MPI underestimates the velocity, Eq. (5b) yields maximum air velocity which decrease with surface air enthalpy! The velocity increase of (5a) is due to increased work of expansion (E_s); the velocity decrease of (5b) is due to decreased enthalpy difference ($k_s - k_a$).

Emanuel uses the temperature at the top of the troposphere for the cold source temperature. Renno (2008) used the average temperature of the troposphere as the cold source temperature. Emanuel compared hurricanes to Carnot engine with constant hot and cold source temperatures. Figure 7 shows that the cold source temperature is far from constant. The atmospheric engines is not a Carnot engine; the cooling does not take place at a constant temperature. There are no real Carnot engines. Practical thermal engines are never Carnot engines.

Actual hurricane wind velocity occasionally exceed the Emanuel limit. The discrepancy between E-MPI and observed hurricane Isabel values suggests a significant limitation of E-MPI theory, Montgomery (2005). The *esergy* approach eliminates the discrepancy; and the need for turbo-boost injection of eye air into the eyewall to explain the observed higher intensity.

According to NOAA frequently asked questions (FAQ) and Marks (2003), hurricane upward heat flux is 600 TW based on rain production; and hurricane mechanical energy production is 1.5 TW based on dissipation corresponding to an efficiency of 0.25 %. The total turbine work of 10.4 % in Figure 7 is 40 times greater than the dissipation estimate. This huge discrepancy is because work can dissipate in many ways such as in an unrestrained piston or in flow through an orifice. Hurricane power is proportional to diameter square.

Power in terawatt could be:

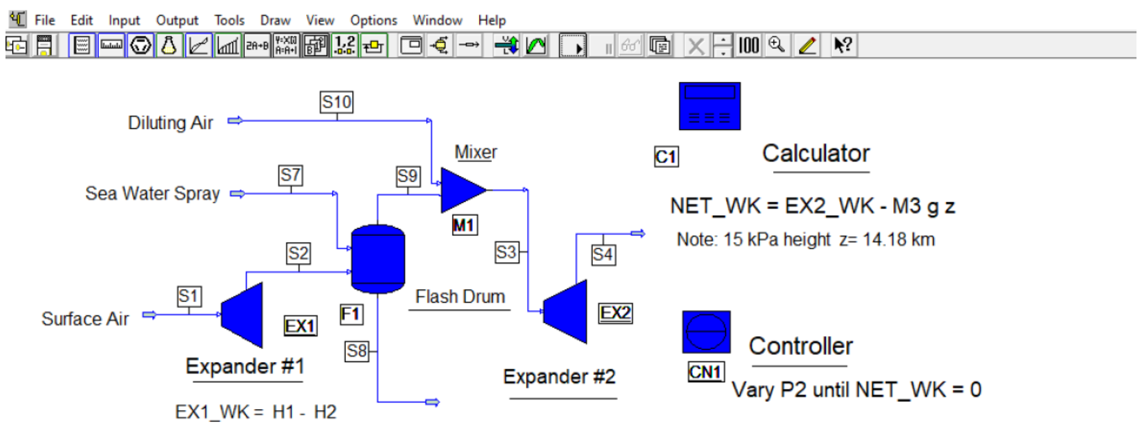
$$P_{TW} \approx 10^{-5} E_S D^2 \qquad (5c)$$

Where D is eyewall diameter in kilometer. A 10 km diameter hurricane with an esergy of 4000 J/kg could produce 4 TW.

600 TW can cool a block of sea-water 60 km wide by 60 km long by 100 m deep by 4.3 K during the 3 hours hurricane passage time over the block. At a heat input of 50 kJ/kg, the upward air flow required to carry 600 TW is ≈12 x 10^9 kg/s. At a spray flow of 24 x 10^9 kg/s, spray cooled by 6°C can account for observed sea cooling. There is no need to consider upwelling of deep water or spray-less sea to air heat transfer, Price (1981).

6. Steady-state engineering process simulator.

Hurricane intensity can be calculated with steady-state engineering simulators such as PRO/II from AVEVA. PRO/II is an easy to use drag and drop simulator for engineers in chemical industries. It has a library of 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 including isentropic expansion of moist air. There is a wide choice of thermodynamic methods. The selected thermodynamic system in Figure 12 and Table 3 is called SIMSCI-SRK. SRK does not use the same zero point as the previous sections. The zero point is not important since work and heat are calculated from enthalpy difference. SRK does not support ice phase; the calculated work is less than with freezing. WR (1993) and Molinari (2012) showed that CAPE for expansion without separation is approximately 50 % less without freezing than with freezing.



Stream Name		S1	S2	S3	S4	S7	S8	S9	S10
Stream Phase		Vapor	Vapor	Vapor	Mixed	Liquid	Liquid	Vapor	Vapor
Pressure	KPA	101.50	98.09	98.09	15.00	105.00	98.09	98.09	105.00
Temperature	C	26.00	23.11	24.63	-58.59	28.00	24.63	24.63	25.00
Total Sp. Entropy	KJ/KG-C	6.47	6.47	6.50	6.50	5.03	4.98	6.50	6.33
Total Sp. Enthalpy	KJ/KG	37.30	34.34	41.83	-97.13	100.67	85.63	41.83	-8.71
Total Mass Rate	KG/SEC	1018.0	1018.0	1020.4	1020.4	500.0	497.6	1020.4	0.0
Total Enthalpy	M*WATT	37.97	34.96	42.69	-99.12	50.33	42.61	42.69	-0.00

Figure 12. PRO/II process simulation. Upper section flowsheet showing units of operation and streams. Lower section stream data table.

Case	T_1	T_2	T_4	M_{w1}	M_{w9}	H_1	H_2	W_{12}	P_2	T_7	T_3 , T_8	M_{w7}	M_{w8}	H_7	H_8	Q_{78}	IE	IE
#	°C	°C	°C	kg/s	kg/s	MW	MW	MW	kPa	°C	°C	kg/s	kg/s	MW	MW	MW	%	Base
Reversible processes – EX1 efficiency 100% - W_{12} is ezergy																		
Ezergy – No water spray - No dilution air																		
1	26	25.01	-64.1	18	18	37.97	34.94	1.03	100.3	--	--	0	0	--	--	0	--	--
2	**30**	27.80	-61.5	18	18	42.14	39.85	2.29	98.93	--	--	0	0	--	--	0	30.2	1
3	26	24.25	-60.4	**20**	20	43.04	40.72	2.32	98.86	--	--	0	0	--	--	0	25.4	1
Effect of water spray – No dilution air																		
4	26	25.03	-63.8	18	18.7	37.97	36.96	1.01	100.3	28	23.56	**5**	4.3	0.50	0.35	0.15	-2.0	1
5	26	24.56	-62.6	18	19.1	37.97	36.47	1.50	99.79	28	23.81	**100**	98.9	10.07	8.11	1.96	24.0	1
6	26	23.11	-54.5	18	20.4	37.97	34.96	3.01	98.09	28	24.63	**500**	487.6	50.33	42.61	7.72	25.5	1
7	26	22.27	-55.4	18	21.6	37.97	33.79	4.18	96.78	28	25.28	**1000**	996.4	100.67	88.22	12.35	25.5	1
8	26	21.75	-51.6	18	22.9	37.97	32.48	5.49	95.34	28	26.03	**2000**	1995.1	201.33	183.31	18.02	24.7	1
9	26	21.27	-48.0	18	24.3	37.97	31.31	6.66	94.06	28	26.72	**4000**	3993.7	402.66	379.34	23.32	24.1	1
Effect of ambient air temperature and mixing ratio with 500 kg/s water spray																		
10	**30**	26.29	-56.4	18	21.2	42.14	38.28	3.86	97.19	28	25.07	**500**	496.8	50.33	43.53	6.80	27.4	6
11	26	23.62	-56.0	**20**	21.3	43.04	39.07	3.97	97.03	28	25.15	**500**	498.7	50.33	43.67	6.66	25.6	6
Effect of air dilution – 200 kg/s 25°C air with 10 g/kg mixing ratio																		
12	26	23.44	-59.7	18	23.5	37.97	35.30	2.67	98.47	28	25.56	**1000**	996.5	100.67	89.47	11.20	-13.5	7
Irreversible processes – EX1 efficiency 0.02% - W_{12} is dissipated work - IE = (Inergy – Ezergy)/Ezergy in percent.																		
13	26	25.99	-63.2	18	18	37.97	37.97	1.46	99.83	28	25.99	**0**	0	--	--	0	42	1
14	26	25.99	-56.6	18	21.1	37.97	37.97	3.73	97.28	28	26.03	**500**	496.9	50.33	43.44	6.89	24	5

Table 3. PRO/II simulations results. P1 = 101.5 kPa, P4 = 15 kPa in all cases. Figure 12 shows case 5. Incremental efficiency (IE) is 25 % of increase in latent heat and 30 % of increase in sensible heat.. 98.9 % and 99,8 % of spray fall back in the sea in cases 4 and 8 respectively. The spray is cooled by 4.19°C and 1.28°C in cases 4 and 8 respectively. Spray effectiveness decreases with spray flow mainly because spray ΔT and affinity both decrease.

The atmosphere is not a steady-state system, but PRO/II can be used to explain the energy of storms. Energy calculations are in per kilogram of air in the previous sections and per kilogram per second in the PRO/II simulation. The total flow of 1018 kg/s at the bottom of the table consist of 1000 kg/s of pure and 18 kg/s of water vapor corresponding to a relative humidity of 85 %. At an air flow of 1000 kg/s, a power output 3 MW corresponds to a specific work 3 kJ/kg-air.

Stream data such as pressure, temperature and composition are entered by clicking on the stream. Unit of operation data such as expander outlet pressure and efficiency are entered by clicking on the unit. Clicking the arrow on the top tool bar carries out the calculation and fills in the stream property table below the flowsheet.

Isentropic expansion is represented by expanders EX1 and EX2. Calculator C1 calculates the potential energy in the final state. A look up table based on the Jordan sounding is used to determines Z_4 based on P_4. Controller CN1 finds the value of P_2 required to make EX2 work equal to the final potential energy. Sea-spray is represented by optional stream S7 and flash drum F1. Flash drum F1 is an isenthalpic mixer; its two outlet streams are in equilibrium. Dry air dilution is represented by optional stream S10 and mixer M1.

Table 3 shows results for several cases. Results agree with the ezergy method. Steady-state simulation make it easy to distinguish between the significant and the unimportant.

- *Without spray,* W_{12} increases with the temperature and with the mixing ratio of ambient surface air.
- *With spray,* W_{12} 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, 100 % relative humidity.
- Approximately 99.5 % of the spray falls back in the sea at a temperature up to 5 °C lower than the sea temperature thus transferring a huge quantity of heat from sea to air.
- The temperature of the air leaving the flash drum increases with spray flow and temperature.
- Incremental efficiency (IE) is 30 % for dry heat and 25 % for wet heat.
- The efficiency of the first expander can be decreased from 100 % to 0 % to check the effect of irreversibility.
    - For ambient air sensible heat input, inergy is 42 % higher than ezergy,
    - For heat supplied by water spray inergy is 24 % higher than ezergy.
- Mixing unsaturated air with the rising saturated air (S_{10}) reduces work and relative humidity.
- Large water spray (S_7 = 10 to 4000 kg/s) increase the air temperature because the latent heat is provided by the water.
- Very small water spray (S_7 < 5 kg/s) decrease air temperature to the ambient air wet bulb temperature because the heat of evaporation is supplied by the air. Increasing EX2

discharge pressure P4 from 15 t0 80 kPa show that small quantities of spray can make evergy neap (CIN) more negative and inhibit convection.

- The latent heat content of ambient air (S_1) is large compared to the latent heat provided by the spray.

The PROII simulation shows that saturated air of any temperature up to the SST can be produced by increasing the water flow F7. In the PROII simulation spray flow, F7, is specified. In the esergy simulation of Figure 10, the updraft temperature T3 is specified; the spray mass flow F7 and the spray to air mass flow ratio are back calculated.

7. Conclusion

Richard Smalley, who won the 1996 Nobel Prize of Chemistry, wrote: *"Without finding an abundant source of clean energy, there is no hope of stopping climate change."* Humans will not accept reduced energy availability; we must find a new energy source.

There is an urgent need for clean renewable energy; atmospheric upward convection could provide clean energy. The atmosphere could produce 6000 TW by converting 12% of its upward convective heat flux to mechanical energy, Michaud (AVE-FAQ). The heat required to produce the work is already stored in surface air and in sea water. There is no need for large area solar energy collectors. The existing heat content of ambient air and warm sea water could produce much more power than humans require.

The vortex prevents loss of buoyancy by dilution and transfers work of buoyancy downward. The pressure reduction at the base of the vortex could drive turbines producing shaft work and electricity. Controlled anchored vortices would not be dangerous and could be used to produce clean power, to reduce local temperature, or to make the rain fall where needed.

There is a potential for producing mechanical energy when moist surface air is raised to the tropopause. The ideal work (ezergy) of surface air is typically 1000 to 2000 J/kg. Ideal work could be increased to ≈5000 J/kg by spraying the air with warm tropical sea water or with low temperature waste heat. Surface air can be in a metastable wherein a short duration energy input can overcome initial negative buoyancy and enable the exergy to be captured at grade. Heat input and rotation could be controlled at grade.

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 5 km to produce significant ezergy. The vortex must be controllable and stable. There are many possible configurations, see Michaud (1975, AVE2007, AVE2021). A concerted development program would quickly find out what works. We cannot control natural storms, but we could learn to produce well controlled atmospheric vortices.

There are wide differences in estimates of atmospheric efficiency and maximum work production potential. Peer reviewed efficiency range from 0.7%, Kleidon (2021), to 40%, Bister and Emanuel (1998). Maximum efficiency estimates can differ by a factor of 60 to 1. Renno's (2008) efficiency estimate of 15% is in accord with the present ezergy approach.

Margules figured out how wind energy is produced in 1903. Margules (1906) wrote: "I hold vertical movement under the influence of gravity to be the essential cause of storms. The energy potential of horizontal pressure difference is very small. The energy source is not to be found in gradients but in the rising of warmer or moister air."

Margules (1906) calculated the maximum work produced when saturated air is raised and for one case and obtained results that agree with the present *ezergy* method. He wrote: "Man could gain a closer understanding, when better methods than presently known, for the handling of aerodynamic problems are found." He quoted the Ostwald axiom: "The simplest explanation always comes last."

Some atmospheric scientists do not recognise that vertical heat flux is responsible for horizontal wind and for poleward energy transport. There are recent peer reviewed articles claiming that wind energy is the result of horizontal and not vertical temperature gradient and that the maximum available wind energy is at as low as 0.5 W/m^2, corresponding to a maximum wind energy production of 250 TW. The energy potential of upward heat flux is 24 times that of horizontal heat flux. Based on horizontal heat flux, horizontal temperature difference, and wind turbine efficiency, the maximum wind efficiency is 0.76 % of the poleward heat flux of 33,000 TW corresponding a maximum wind energy production of 250 TW. Figures 2 and 7 show that vertical upward flux can contribute to horizontal wind production.

Engineers know that producing energy from a small temperature between heat source and sink located at the same elevation is difficult; more so when the source and sink are thousand of kilometers apart. Engineers regularly reject low temperature waste heat without trying to capture its work production potential. Thermosyphons wherein the heat sink is above the heat source are widely used to produce circulation, including flow in horizontal conduits, from low differences in temperature.

The current world electrical power production of 3 TW could be provided by 1500 2 GW AVE's with a total station area of 1500 km^2; the collector is the earth's surface in its natural state. Photovoltaic at an efficiency of 10% could require a collector area 300 000 km^2.corresponding to 0.6% of the earth's surface area. Photovoltaic could require 200 times more area than AVE. The long-term environmental effect of AVE's would be like that of natural vortical storms and would be minor compared to those wind or photovoltaic. Wind turbines could already be affecting climate by reducing wind. AVE's might improve weather and climate by controlling where and when precipitation occurs.

The horizontally driven wind energy theory with its maximum energy production potential of 0.5 W/m^2 would require 6,000,000 km^2 to produce 3 TW - 1.2% of the earth surface, 3.6% of the land surface, and over 20% of the crop growing surface. The horizontally driven theory can not be correct, existing wind farms can produce over 10 W/m^2.

Engine efficiency is calculated by following a fluid through idealized closed 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 for different cases easily comparable.

Calculating efficiency from models is difficult. 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 and not on how much work could be produced if the convection process were controlled. Engine efficiencies are calculated using idealised processes; calculating velocities, flow pattern, dissipation adds unnecessary complications.

The energy of hurricanes is due to enthalpy transfer from the underlying warm sea. The Lorenz (1967) reference state approach provides little 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 in an expander located at grade. The thermodynamic basis is well established. Engineering tools such as PRO/I, designed for use on any continuous steady-state process including wet cooling towers, can be used to understand atmospheric convection.

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). To do so will require academic institutions to demolish some of the stovepipes (e.g. between science and engineering) that currently discourage basic researchers from more fully engaging in the practical problem of risk assessment, Emanuel (2018).

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

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

Appendix A

PROPOSED MECHANICAL ENERGY NAMES

In ideal processes, mechanical energy can be transformed from one form to another without loss. The names Free Energy and Ideal Work have been uses for the mechanical energy produced by a variety of processes. In this paper, distinct names are used to avoid ambiguity. The new mechanical energy names are based on the process by which the work is produced and are extensions of the Rant naming system.

Existing name

Exergy (E_x *or A*) 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 between the 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. The concept was developed by Willard Gibbs in 1873, who used the name **Ideal Work**; it was renamed **Exergy** by Zoran Rant, in 1951. The usual symbol for ezergy is ***"A"*** from German Arbeit. The $g\Delta z$ term is zero for processes where there is no change in elevation. Exergy is mainly used in processes involving chemical reactions.

Proposed new names

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

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

The final temperature and enthalpy can be calculated from known final pressure with a solver. **Exergy** is greater than **ezergy** 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. *E**x**ergy* (E_x) is dependent of the temperature of final environment. *E**z**ergy* (E_z) is independent of the temperature of final environment.

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 subscript "***m"*** stands for same (même), no change in elevation ($\Delta z = 0$).

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

Esergy (E_S) is the maximum work that can be produced by air that has been sprayed with warm water. The subscript "***s"*** stands for spray. *Esergy* is larger than ezergy because air can 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, usually a more poleward location. The subscript ***"p"*** stands for poleward.

Imergy (E_i) is the work produced and dissipated in a fully irreversible moving process. The subscript **"I"** stands for irreversible.

Subscripts and Defaults.

Free energy type can be further specified with 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). Exergy equivalent.
$E_{s(26\text{-}90\text{-}15)} = E_v$ 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 noverhead.

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AVEVA PRO/II Simulation – The Trusted Steady-State Process Simulator

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V2. The Action Lab. https://www.youtube.com/watch?v=b1bOnD8v5sk
V3. Singapore Science C. https://www.youtube.com/watch?v=fwzKpKHRYo8&t=69s
V4. Burning Man. https://www.youtube.com/watch?v=nSJkydvQTJY
V5 Lambton College AVE https://youtu.be/_HoP6ZMdLSw
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