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Research Article

Climate emergency-focused economic model

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Abstract: This paper deals with the existing carbon dioxide mitigation efforts toward the Paris agreement and shows that current economic rules and the first law of thermodynamics, all of which are linear, are necessary but not sufficient tools to solve the nonlinear problems of global warming. In this respect, the quasi-linear, Pareto principle-based green economy has been modified by the second law of thermodynamics, which deals with the useful work potential of energy systems and resources for added value in society, aka exergy. It is argued that the aged Pareto principle, which may only associate with the first law of thermodynamics, recognizes less than half of the total root causes of emissions. For example, fossil fuels are currently treated as a simple economic commodity in the stock market, subject to market rules rather than environmental parameters, whereas exergy destructions are the primary root causes of emissions. A new model was developed for evaluating and rating green energy systems, which calculates the exergy destruction-based emissions and optimizes systems for minimum emissions. Five cases are presented to quantify the face value of the Pareto principle against renewable energy resources and systems. These cases are, namely, solar energy, wind energy, geothermal energy with organic Rankine cycle, heat pumps, and Fresnel lenses for photovoltaic panels. Sample results show that the Pareto principle may not rate these systems because its equivalent unit exergy value (0.21 kWh/kWh), also described as virtual Pareto temperature (363.9 K), is less than the unit exergy of renewable energy systems under their normal domain of operations. One of these results regarding wind energy is that the 80/20 Pareto principle has equivalent unit exergy of 0.21 kW h_{exergy}/kW h_{energy}, corresponding to a wind velocity of three meters per second, which is less than the practical cut-in speed of a conventional wind turbine. Therefore, the Pareto principle may not be a measuring stick for wind energy and other resources. It has also been shown why the global average of rational exergy management efficiency of 0.21 is not improving because the Pareto principle limits it.

***Keywords**:* *Carbon mitigation, Climate emergency, Concentrating solar, Exergy-based economic model, Exergy destructions, Fresnel lenses, Geothermal cogeneration, Pareto temperature*

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Nomenclature

Symbols	
a	Constant of Eq. 1
A_p	Solar panel area, m^2
AV	Added value for the society (Useful work potential, exergy), kW h/kW h
c	Carbon content, kg CO_2/kW h
CR	Area concentration ratio
C_E	Cost of electricity, $/kW h
c_H	Cost of heat, $/kW h
c_K	The carbon content of the fuel, kg CO_2/kW h
CO_2	Direct carbon dioxide emissions, kg CO_2/kW h of exergy input
COP	Coefficient of performance
d	The ratio of emission responsibility to the equivalent emission mitigation
E	Energy, kW h
E_x	Exergy, kW h
GWP	Global warming potential
I	Investment cost, $
I_n	Solar insolation, kW/m^2
k	Constant of output energy and efficiency relation (Eqs. 3, 4)
LCA	Life-Cycle Analysis (Payback in years
$LCCA$	Life-Cycle Carbon Analysis
$LCEA$	Life-Cycle Energy Analysis
$LCEXA$	Life-Cycle Exergy Analysis
$LCODIA$	Life-Cycle Ozone-Depletion Index (*ODI*) Analysis
m	The slope of the Pareto line
ODP	Ozone depletion potential
ODI	Ozone depletion index
P	Parasitic power, kW h
p	Equivalent concentration penalty (due to parasitic cooling power for PV panels)
P_e	Pareto emission factor, $CO_2/(\varepsilon_{sup}\cdot 0.63)$. 0.63 is the sector average emissions rate
PEF	Primary energy ratio
Q	Energy input, kW h
$\dot{Q}$	Annual heat generation, kW h
R_{EX}	Exergy-based share of renewables
T	Temperature, K
t	Time, s
U	The quasi-linear utility function of Pareto
v	Time-dependent variable (Eq. 1)

Greek Symbols	
ΔCO_2	Nearly avoidable CO_2 emissions due to exergy destructions, kg CO_2/kW h
ΣCO_2	ΔCO_2+CO_2
ΔT	Temperature difference, K
ε	Unit exergy, kW h/kW h or kW/kW
ψ_R	Rational exergy management model (REMM) efficiency
η_I or η	First law efficiency
η_{II}	Second law efficiency

Subscripts			
B	Boiler	in	Input
c	Cooling	H	Heat
dem	Demand	op	Operational
des	Destroyed, destruction	out	Output
E	Electricity	PP	Power plant
em	Embodied	PV	Photo-voltaic
f	Fuel, source (temperature), or virtual	ref	Reference
FPC	Flat-plate collector	sup	Supplied, supply
FL	Fresnel lens	W	Wind
FPC	Flat-plate collector	WT	Wind turbine
g	Geothermal		

Acronyms	
ADS	Adsorption (Cooling Machine)
BAU	Business-As-Usual
CCS	Carbon Capture and Storage
5 DE	Fifth-Generation District Energy System
DHW	Domestic Hot Water
DRA	Drag-Reducing Agent
EGEC	European Geothermal Energy Council
EIA	US Energy Information Agency
EU	European Union
FPC	Flat-Plate Hot W ater Collector
HP	Heat Pump
IEA	International Energy Agency
ORC	Organic Rankine Cycle
PV	Photo-Voltaic
PVT	Photo-Voltaic-Thermal
PVT3	Third-Generation (Advanced) PVT
REMM	Rational Exergy Management Model
TES	Thermal Energy Storage

1. INTRODUCTION

1. Current Economic Rules Does Not Respond to the Paris Agreement.

2. Economic Principles Change but Thermodynamic Laws do not.

Current decarbonization efforts, led by the green deal action plan and green financing, depend on linear functions. For example, the Pareto principle, which is based on the linear 80/20 proportion with a history of more than a century, still governs simple economics and green investment of today, is linear or quasi-linear, as shown in Eq. 1 and depicted in Fig. 1. The fundamental utility functions, *U* in Pareto efficiency (elasticity), are linear or quasi-linear.

$$U(t,a) = v(t) + a \tag{1}$$

Any elasticity in the efficiency, η_I, given in Eq. 3, is linearly proportional to the energy output, E_{out} for the energy input E_{in}. Energy is a simple commodity or asset in a simple economy. Efficiency affects only investment returns. A comparison of the linear equations (Eqs. 1, 3) with the nonlinear one (i.e., Eq. 5) shows that the Pareto principle, simple economy, and the first law are incompatible with nature and the second law of thermodynamics.

$$\eta_I = \frac{E_{out}}{E_{in}} \tag{2}$$

$$\Delta\eta_I = \frac{\Delta E_{out}}{E_{in}} = k\Delta E_{out} \ \textit{\{Linear relationship\}} \tag{3}$$

$$k = 1/E_{in} \tag{4}$$

The Pareto principle does not apply to the green deal, subject to the second law of thermodynamics (exergy). The ideal Carnot cycle (Eq. 5) is nonlinear, and the elasticity of unit exergy, ε_{i+1}, is a second-order function (Eq. 6) of the source temperature, T_{fi} of any system in the $(i)^{th}$ step of a chain of energy process, or change in the urban land-use efficiency.

$$\varepsilon = \left(1 - \frac{T_{ref}}{T_f}\right) \ \textit{\{Unit exergy\}} \tag{5}$$

$$\Delta\varepsilon_{i+1} = \left(1 + \frac{T_{ref}}{T_{fi}^{\,2}}\right)\Delta T_{f\,i+1} \ \textit{\{Nonlinear relationship\}} \tag{6}$$

According to Eq. 6, all changes, in this case, are positive and depend on the history of source temperature concerning a given mix of energy sources by a “Square Law”. On the other hand, according to Pareto, one $+T_f$ simply requires one $-\varepsilon$. On the contrary, Eq. 6 shows that any positive change (Increase) in source temperature results in a positive exergy increase. All changes, in this case, are positive and depend on the history of source temperature changes about an optimal mix of energy sources by a “Square Law” (T_{fi}^2).

2. LITERATURE SURVEY

Current economic principles only deal with the quantity of energy (The first law of thermodynamics), which is traded as a simple economy in the stock market. For example, electricity is treated as a cost item in the day-ahead price indexing systems [1]. In such a system, as described in [1] by Kölmek and Navruz, the ARIMA variables involve only linear terms. They are used only for price forecasting without considering or investigating the quality of energy behind the electricity generation, like fossil fuel-based power plants, solar energy, or wind energy. According to EIA (US Energy Information Administration) [2], there are five major factors in determining the electricity market (The thermal energy market is not regulated yet, which is a very important gap in the literature). All of these factors depend only on the first law of thermodynamics and have linear relations:

- *Fuel cost*
- *Power plant investment payback and operating cost*
- *Transmission and distribution system maintenance and operating costs*
- *Price regulations*
- *Demand and supply quantities (First law)*

It is noteworthy that four of the five factors mentioned herein are directly related to simple cost, and the last factor is constrained by the first law of thermodynamics (quantity). Therefore, the current economic principles cannot address the environmental concerns and cannot provide sustainable solutions even with the so-called green financing because they are all linear and do not recognize the quality of energy and related CO_2 emissions according to the second law.

Fig. 1 shows that the market economy is much less responsive to the "quality" of the source in terms of T_f in Eq. 5. Therefore, the added value of an energy source in terms of its quality (exergy) is largely devaluated. For example, the *AV* of a thermal energy source at a source temperature of 345 K (or Carnot-Cycle-equivalent virtual source temperature for mechanical systems) with exergy of (1-283 K/345 K) = 0.179 kW h_{exergy}/kW h_{energy}, the current economic rules in the literature can only predict a much lower added value potential for the socio-economic and environmental domain by 0.03 kW h_{exergy}/kW h_{energy}. Similarly, the linear (or quasi-linear) Pareto principle-based simple economy has almost a constant sensitivity and cannot distinguish the difference between the temperature-dependent sensitivity (elasticity).

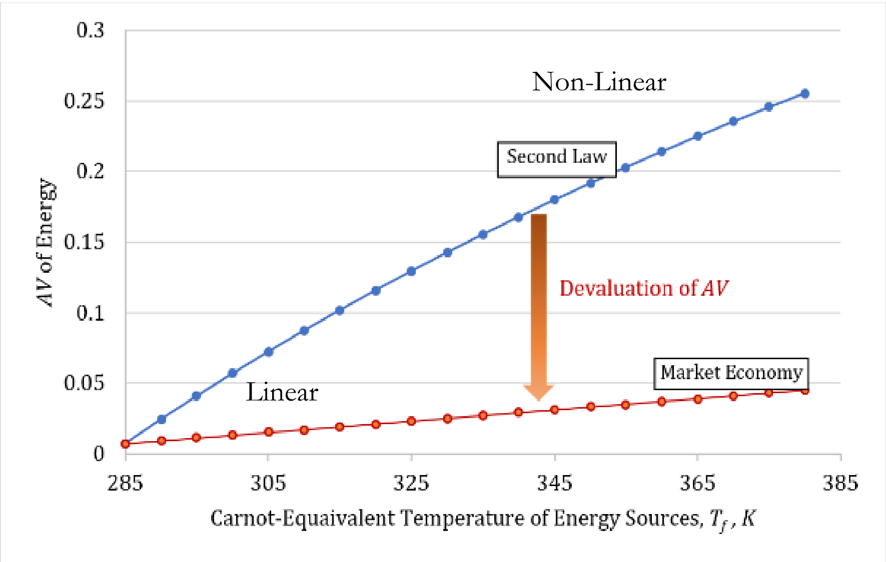

Figure 1. Devaluation of the Added Value Potential (Exergy, ε), AV in Linear Market Economy.

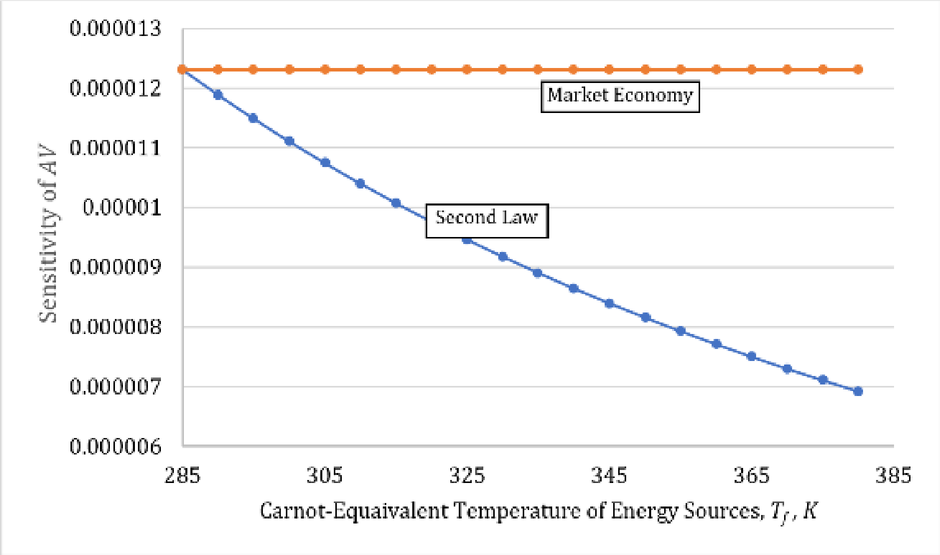

Figure 2. Pareto-Led Market Economy is Insensitive to the Quality of Energy (Exergy)

Therefore, today`s market economy is insensitive to CO_2 emissions predictable from Eq. 7, but the second law can provide the correct guidance to achieve the yet unrecognized sustainable solutions for decarbonization.

$$CO_{2i+1} = c\Delta\varepsilon_{i+1}\left(1-\psi_{Ri+1}\right) = \left[c\left(1+\frac{T_{ref}}{T_{fi}^2}\right)\Delta T_{f_{i+1}}\right]\left(1-\psi_{Ri+1}\right) \qquad (7)$$

Eq. 7 is the emissions elasticity that requires a new set of economic understanding.

3. DEVELOPMENT OF THE MODEL

Fig. 3 shows the complexity of the root causes of emissions concerning a system that generates power. Exergy destructions at several points create a history of unrecognized root causes of emissions and CO_2 due to exergy destructions. Fig. 3 shows two forward echoes of emissions (Boiler and PV panels to offset the thermal exergy destruction of the system partly) and one echo backward (to offset the thermal exergy destruction at the power plant by an array of PV systems). The total CO_2 emissions responsibility is usually more than the net direct emissions responsibility or savings, $\pm CO_2$. Therefore, any system that seems economical and environmentally friendly may not be so according to the second law.

Despite the importance of the second law, city planners and energy strategists keep insisting on a simple and linear relationship between decarbonization and cost [3]. In this respect, the report by New Buildings Institute (NBI) presents incremental first cost and life cycle cost of two common building types. They examined the cost-effectiveness of the all-electric and mixed-fuel paths in the Building Decarbonization Code for Climate Zone 5A (a comparatively cold climate) in the US. The report claims that an all-electric single-family home is the cheapest to construct. They have also found that 90-97% of the cost increase is attributable to the on-site electric vehicle charging stations. In the latter case, electric vehicles, except electric mass transport, are not environmental yet [4]. Furthermore, solar PV panels are responsible for $\pm CO_2$ emissions, while they destroy the thermal exergy of the solar input. When these claims and findings are compared with the scope of this paper, it is evident that the Paris agreement goals may not be reached with such simplistic and linear economic rules and mindset.

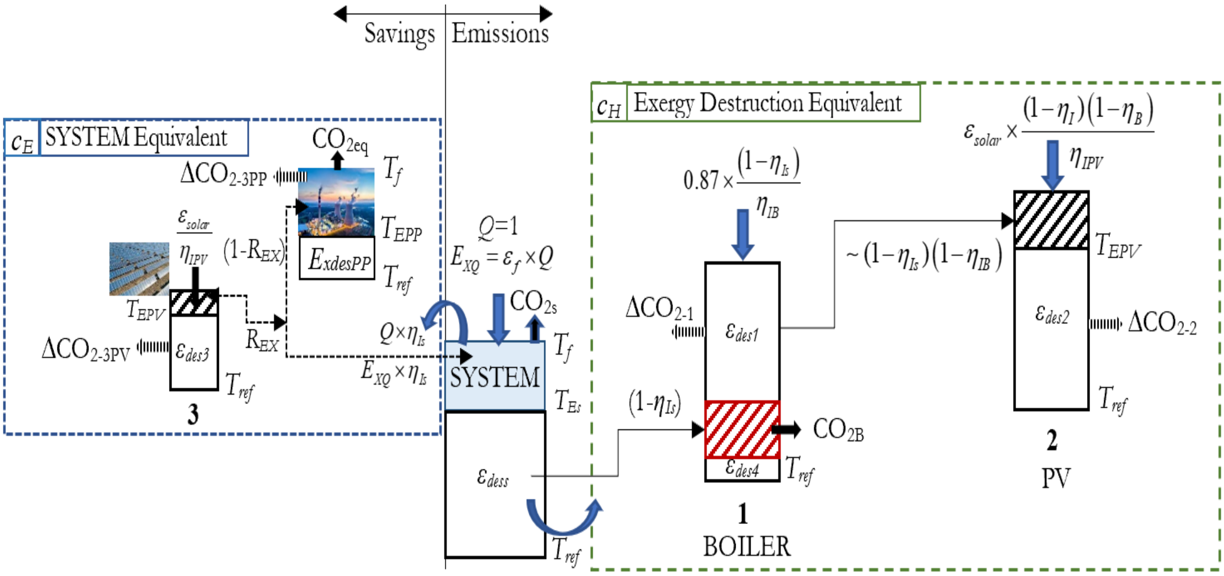

Figure 3. CO_2-Calculation Model, with Three Generations of ΔCO_2 Emissions in the Background and the Direct Emissions. The System Generates Power Upstream and Destroys Thermal Exergy Downstream. εdes4 is neglected [4].

Fig. 4 symbolizes today`s Pareto-led simple economy. Here, finance dominates, and it is a top-to-bottom process where environmental and social issues are slave functions of the economy. Energy is a subset of the economy. At the same time, the environment is protected as long as the market economy permits. For example, a flat-plate solar collector for domestic hot water production is the cheapest and simplest solar energy system with almost the highest first-law efficiency. Naive users may prefer flat-plate solar collectors because they are "cheap and efficient". See Fig. 5. However, these panels destroy power generation opportunity (exergy destruction) like a PV cell could generate upstream, and therefore most solar exergy is destroyed and are responsible for ΔCO_2 emissions. Therefore, they are cheap and highly efficient in terms of the first law but not environmentally rational in terms of the second law. A responsible user should prefer such an advanced PVT: an advanced solar PVT system with comparable efficiency mitigates CO_2 yet is the most expensive panel in the market. After all, it may recover its embodied emissions with negative operational emissions soon, whereas a solar flat-plate collector may recover its investment cost soon but may never recover its carbon embodiments because its operational emissions responsibility is positive. Fig. 1 also points out where the simple economy of "green buildings" is [3].

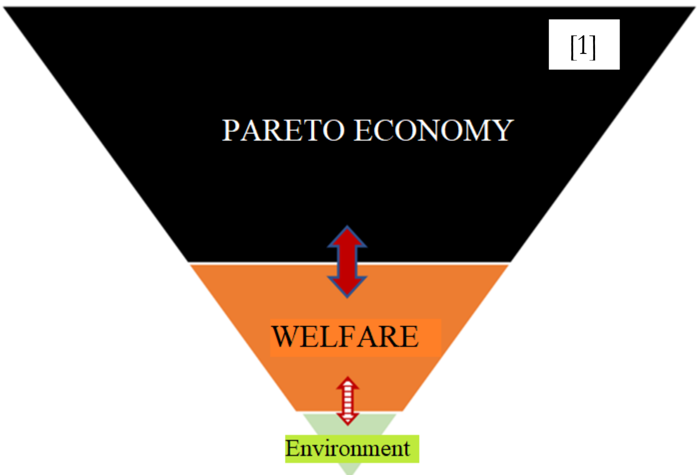

Figure 4. Linear, Pareto-Led Society and Environment.

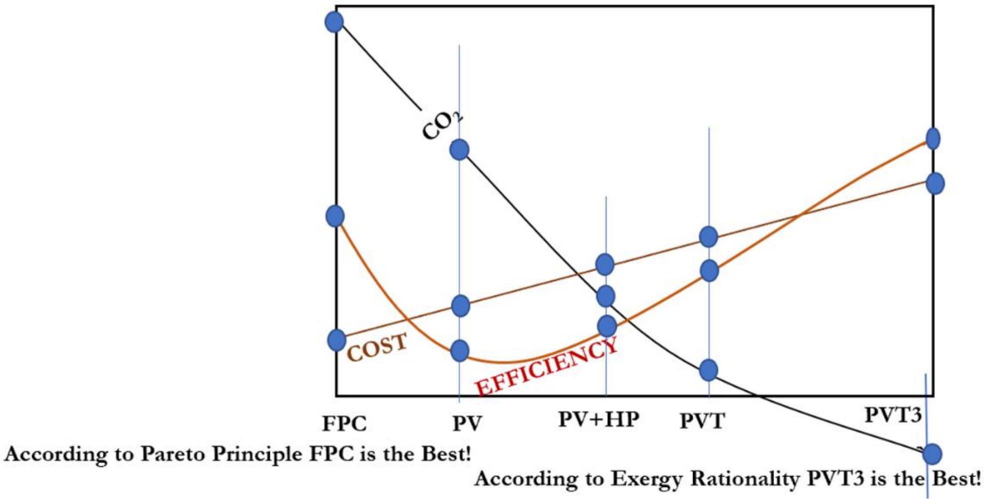

Figure 5. Choice of Non-Concentrating Solar Panels According to the Simple Economy and Exergy-Based Economy [4].

As a result of these discussions, it may be concluded that five major steps are necessary to facilitate satisfaction of the Paris agreement goals on time:

1) *Decouple simple economy from welfare, environment, and energy (see Fig. 6),*
2) *Develop a bottom-up solution starting with energy and exergy (see Fig. 6) by releasing the energy and exergy elements of decarbonization from the simple economy as separate but interrelated subjects of concern,*
3) *Associate exergy destructions with CO2,*
4) *Develop new exergy and carbon-based life-cycle assessment equations,*
5) *Define the Pareto economy in terms of the Carnot cycle (Pareto temperature) and reattach it to form the quadrilemma.*

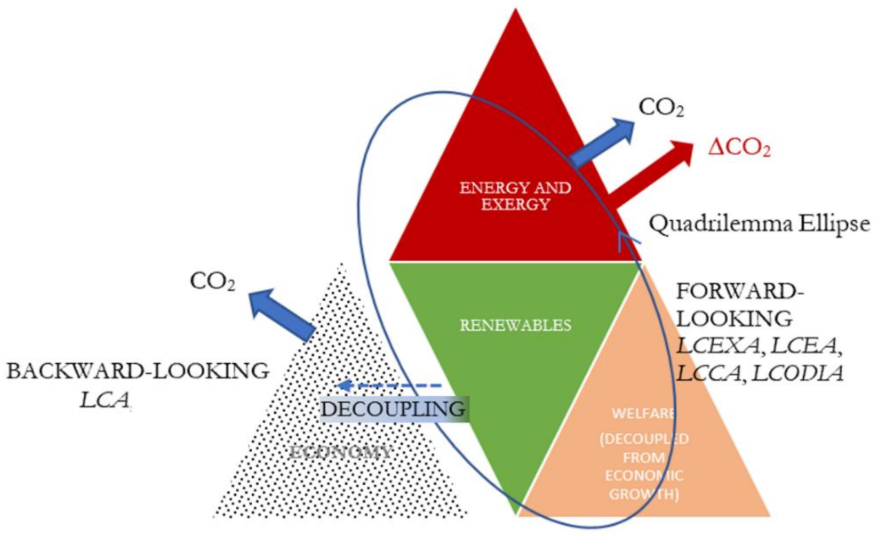

Figure 6. Second-Order Quadrilemma Ellipse of the Decarbonization Loop [4]

In summary, the conflicting elements of the simple economy, namely economy, welfare, and environment (in simple economic rules), must be expanded to four subjects after converting the Pareto principle and reattaching back to a common Carnot platform, which emerges into the exergy-closed decarbonization loop. In this loop, a new understanding of climate crisis, the priority is given to the energy and exergy that primarily affects global warming contrary to the simple financial economy.

4. CLIMATE EMERGENCY-FOCUSED ECONOMIC MODEL

This model shows that Life-Cycle Analysis with simple energy and carbon trading cannot satisfy the goals of the Paris agreement.

Hypothesis 1: Pareto principle has unit exergy equal to $\psi_{Rref,}$ the universal reference value of the rational exergy management efficiency in the built environment [5].

Hypothesis 2: Paris agreement goals may only be achieved by the second law of thermodynamics.

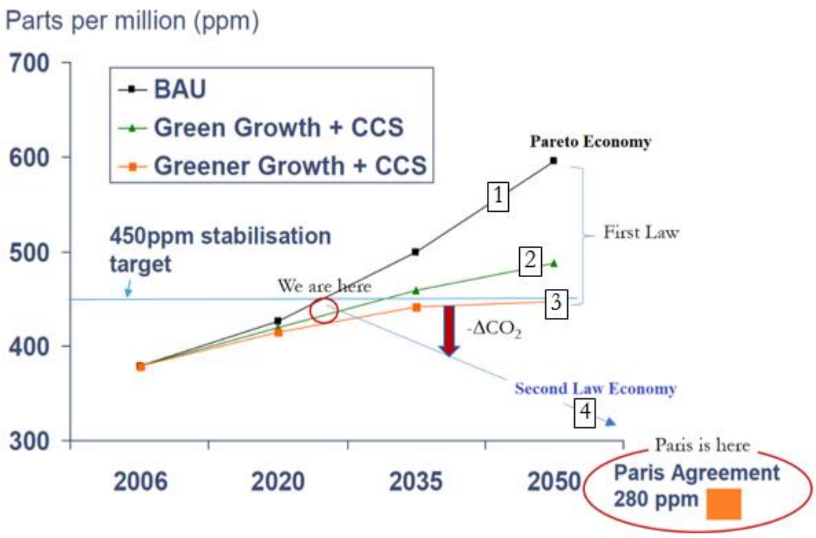

Figure 7. Trends of CO2 Content in the Atmosphere for Different Scenarios. Scenario 4 corresponds to Fig. 6 (Quadrilemma Ellipse).

STEPS 1 and 2 - Decoupling and Bottoming Up

These two steps have already been shown in Fig. 6. The four elements of the quadrilemma ellipse are brought to a common thermodynamic platform defined by the ideal Carnot cycle. For wind and solar energy, the virtual source temperature, $T_{f,}$ is given by Eqs. 8 and 9, respectively.

$$T_{f_{solar}} = \frac{T_{ref}}{\left(1 - \frac{I_n \times 0.95}{1360.8}\right)} \tag{8}$$

$$T_{f_{wind}} = \frac{T_{ref}}{(1 - 0.95 \times \eta_{WT})} \tag{9}$$

$$\psi_R = \frac{\varepsilon_{dem}}{\varepsilon} \tag{10}$$

Any increase in source temperature with optimal renewable mix provides more room for better and a variety of useful applications with minimum waste in an array. This approach guides minimum exergy destructions by stacking maximum useful applications, leading to maximum REMM efficiency [6]. Therefore, Eq. 11 draws the decarbonization roadmap and shows what rational steps should be taken.

<u>STEP 3- Associate Exergy Destructions with CO_2</u>

This is especially important for renewable and waste energy systems with low-enthalpy (exergy) towards the Green Deal approach [7], which handles CO_2 emissions within a constraining scope of carbon trading, and the Paris Agreement [8].

$$CO_2 = c\varepsilon_{des} = c\varepsilon_{\sup}\left(1-\psi_R\right) \tag{11}$$

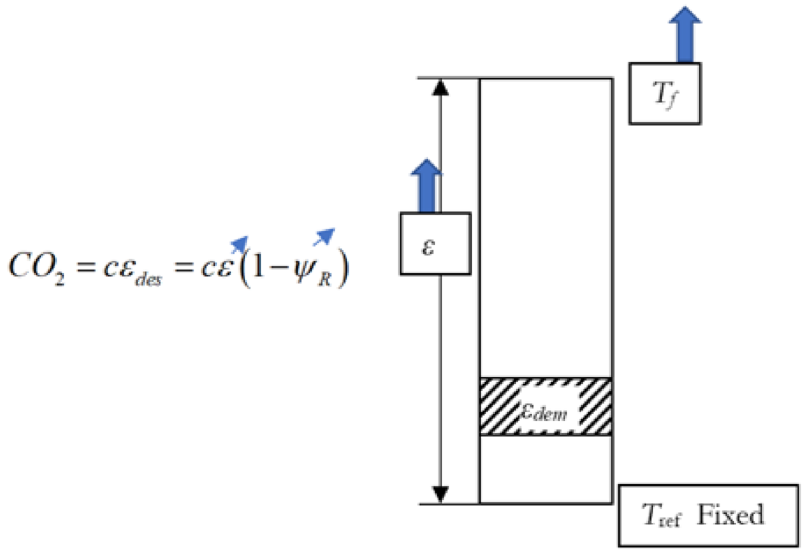

Figure 8. Nonlinear Exergy Relation on Exergy Flow Bar

$$CO_{2i+1} = c\Delta\varepsilon_{i+1}\left(1-\psi_{Ri+1}\right) = \left[c\left(1+\frac{T_{ref}}{T_{fi}^2}\right)\Delta T_{f_{i+1}}\right]\left(1-\psi_{Ri+1}\right) \tag{12}$$

Although supply exergy increases, REMM efficiency increases faster, provided that rational stacking of useful applications in a row is made in an array. The net result is reduced pollution, which is not a concern for the Pareto principle.

This emission equation, according to the second law, is also nonlinear and cannot be explained by simple economic theories of the last century, like the Pareto rule. Instead, this equation provides a valuable tool to optimize the renewable energy mix for minimum emissions, independent of the economy. Today environmental issues are priorities far above simple economic rules. In the future, if environmental conditions become favorable, then the economy may regain its importance. Today many politicians have already declared a global crisis. This crisis is much more important than economic crises, mostly due to global warming. Note that Pareto is not predictive of the green deal and is insensitive to the exergy rationality of energy use independently from the economy and application temperatures.

STEP 4- New Life Cycle Equations

Three new metrics are proposed. The fourth metric regarding ozone-depletion potential of refrigerant leaks is eliminated because no heat pumps are used in this model:

1. Life-Cycle Exergy Analysis, *LCEXA*

LCEXA compares the embodied exergy spending during manufacturing and installation plus exergy destructions during operation with net exergy supply from renewables.

$$LCEXA = \frac{\sum_{k=1}^{o} Q_{op}^{k}\varepsilon_{op}^{k}}{\sum_{i=1}^{m} Q_{em}^{i}\varepsilon_{em}^{i} + \sum_{j=1}^{n} Q_{op}^{j}\varepsilon_{des}^{j}} \tag{13}$$

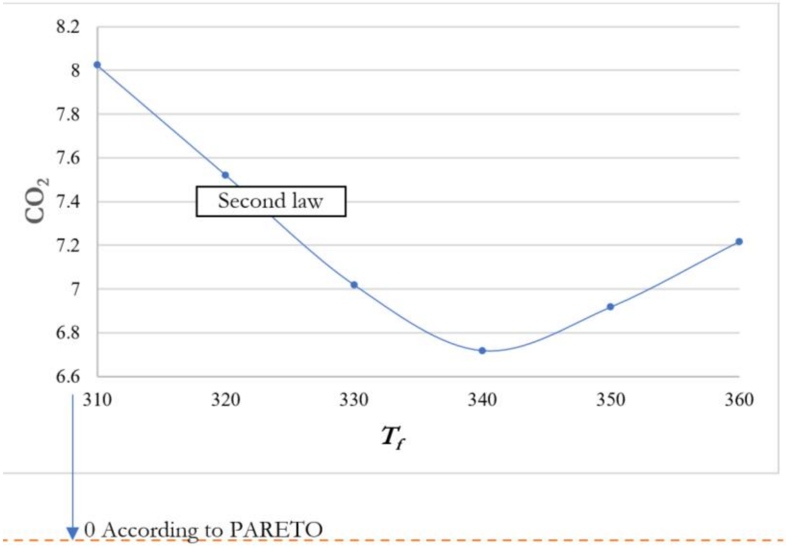

Figure 9. Position of the Pareto Principle versus Exergy Based Emissions Prediction.

2. Life-Cycle Energy Analysis, *LCEA*

LCEA compares the embodied energy spending during manufacturing and installation of green energy systems plus their exergy destructions during operation with the net green energy supply.

$$LCEA = \frac{\sum_{k=1}^{o} Q_{op}^{k}}{\sum_{i=1}^{m} Q_{em}^{i} + \sum_{j=1}^{n} Q_{op}^{j}} \tag{14}$$

3. Life-Cycle CO_2 Analysis, *LCCA*

LCCA covers CO_2 and CO_2, ΣCO_2. *LCCA* is zero if the numerator is not negative (no savings)

$$LCCA = \frac{\sum_{k=1}^{o}\left(\sum CO_{2\,op}^{\;k}\right)_{saved}}{\left[\sum_{i=1}^{m}\left(\sum CO_{2\,em}^{\;i}\right) + \sum_{j=1}^{n}\left(\sum CO_{2\,op}^{\;j}\right)\right]_{responsible}} \tag{15}$$

STEP 5- Mapping Pareto Back to Carnot Cycle

In simple terms and a popular example, 80% of revenue comes from 20% of customers [9]. In other words, out of a hundred customers, 80 customers just generate the remaining 20% of the revenue. The following two-step transformation uses the exergy flow bar [5].

The first bar in Fig. 11 represents that those 20 customers out of 100 customers generate 80% of the revenue. In analogy to thermodynamics, they generate useful work potential. The remaining 80 customers are an analogy to destroyed exergy for the first bar because they are freed up for the second bar. However, the remaining customers make up the remaining revenue of 20% in the second step. Then the two bars are drawn in a cascade in terms of the distribution of the customers. In cascade one, 20 customers are productive for 80% of the revenue. After taking a weighted average with respect to the percentage revenues delivered by each exergy flow bar:

$$\varepsilon_{pareto} = 0.8 \times \varepsilon_1 + 0.2 \times \varepsilon_2 = 0.21 = \psi_{Rref} .$$

Where ψ_{Rref} is calculated as follows, based on natural gas boiler and a generator with C = 1, C is the thermal and power generation ratio, equal in this case.

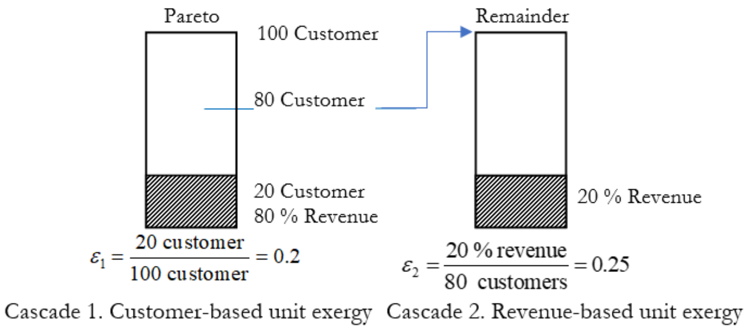

Figure 10. Exergy Flow Bar for Pareto Principle.

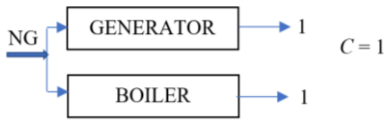

Figure 11. Separate Generator and a Boiler.

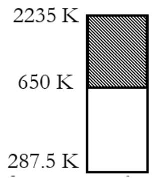

Figure 12. A Typical Exergy Flow Bar for a Natural Gas Driven Power Generator.

$$\psi_{RG} = 1 - \frac{\left(1 - \frac{287.5\text{ K}}{650\text{ K}}\right)}{\left(1 - \frac{287.5\text{ K}}{2235\text{ K}}\right)} = 1 - \frac{0.5576}{0.8714} = 0.36$$

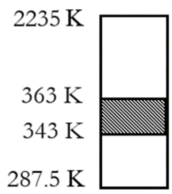

Figure 13. Typical Exergy Flow Bar for a Natural Gas Condensing Boiler.

$$\psi_{RB} = \frac{\left(1 - \frac{343\text{ K}}{363\text{ K}}\right)}{0.87} = 0.0633$$

$$\psi_{Rref} = \frac{\psi_{RB} \times 1 + \psi_{RG} \times 1}{2} = \frac{0.0633 + 0.36}{2} = 0.208 \approx 0.21 \qquad \{Heat\} \qquad (16)$$

Repeating the above calculations for cooling with COP =3 and 7°C (280 K)/12°C cooling regime:

$$\psi_{RHPC} = \frac{\left(1 - \frac{280\ \text{K}}{287.5\ \text{K}}\right)}{(0.95/3)} = 0.0824$$

$$\psi_{Rref} = \frac{\psi_{RHPC} \times 1 + \psi_{RG} \times 1}{2} = \frac{0.0824 + 0.36}{2} = 0.22 \qquad \{Cold\} \qquad (17)$$

For practical convenience, both results may be assumed to be equal to 0.21 to bring heat and cold on the same exergy base. These are the face values of Pareto economics (linear) on a global level of systems and applications involving power, heat, and cold. On the same global level, we use 14.5°C as the average global temperature for T_{ref} (287.5 K).

4.1. Pareto in Solar PV

After defining a virtual Carnot cycle source temperature of market economy and finance:

$$\varepsilon_{pareto} = 0.21 = \left(1 - \frac{287.5K}{T_{f_{pareto}}}\right) \qquad (18)$$

Solving for $T_{fpareto}$:

$$T_{f_{pareto}} = \frac{287.5K}{(1-0.21)} = 363.9\ \text{K} \qquad \{Pareto\ temperature\}$$

This is the Pareto temperature. At this temperature, the Pareto principle corresponds to only 300.8 W/m^2 of solar energy, a very low solar flux. As a rule of thumb, PV systems require a minimum annual solar radiation of 1300 kW h/m^2 [10]. For a moderate sunshine hour of 2000 hours, it corresponds to 650 W/m^2 and a virtual temperature T_f of 526.3 K. Therefore, the second-law face value of the Pareto principle may not rate solar electricity. The same argument also holds for solar hot water. Therefore, such a simple economy may not evaluate energy with higher exergy than 0.21 kW h$_{exergy}$/kW h$_{energy}$, including all renewables. Instead, the economy should be expressed in terms of exergy, depending upon the added value potential of any currency, in terms of a virtual Carnot-based temperature. Therefore, Pareto may not be used for systems and equipment with better REMM efficiency than the reference value, especially green systems. We need REMM efficiency of at least 0.70 for greener growth. Furthermore: $CO_2 = CO_2$ (1- ψ_R). CO_2 for electricity production 0.35/0.52 (1-R_{EX}), for heat generation 0.35/0.85, for cold generation 0.35/0.85/0.8 ABS ADS average in practice (eliminate chiller cooling for future).

Pareto optimal solutions may be useful only if they holistically cover the exergy concept. One of the earliest studies was conducted by Wang, Kilkis, Ş, et al. [11]. A multi-objective optimization approach was applied to the Albano university campus in Stockholm. GHG emissions, the life cycle cost, and the net exergy deficit of the campus were minimized. The solution shows the controversy between economy-oriented and environment-oriented solutions for minimum GHG emissions while net exergy deficit leads to CO_2. The original study did not include the ΔCO_2 term on the right-hand side axis, which is now possible to associate with the net exergy deficit:

$$\Delta CO_2 = \frac{(2.1+1.1)}{2} \times \frac{\text{Exergy Deficit}}{24\ \text{h}} \qquad (19)$$

In an environment-oriented case, the GHG emissions are zero at a simple life cycle cost of 95 SEK/m^2. According to simple economics, this cost is a penalty for environmental concerns. However, according to Eq. 20, the CO_2 term is about 2.93 kg CO_2/m^2. On the other hand, if the high cost is required to be eliminated by an economy-oriented solution, the Pareto front gives about 3 kg CO_2/m^2. In addition, CO_2 is 1.33 kg CO_2/m^2. The total is 4.33 kg CO_2/m^2. Therefore, the economy-oriented Pareto solution yields the highest emissions.

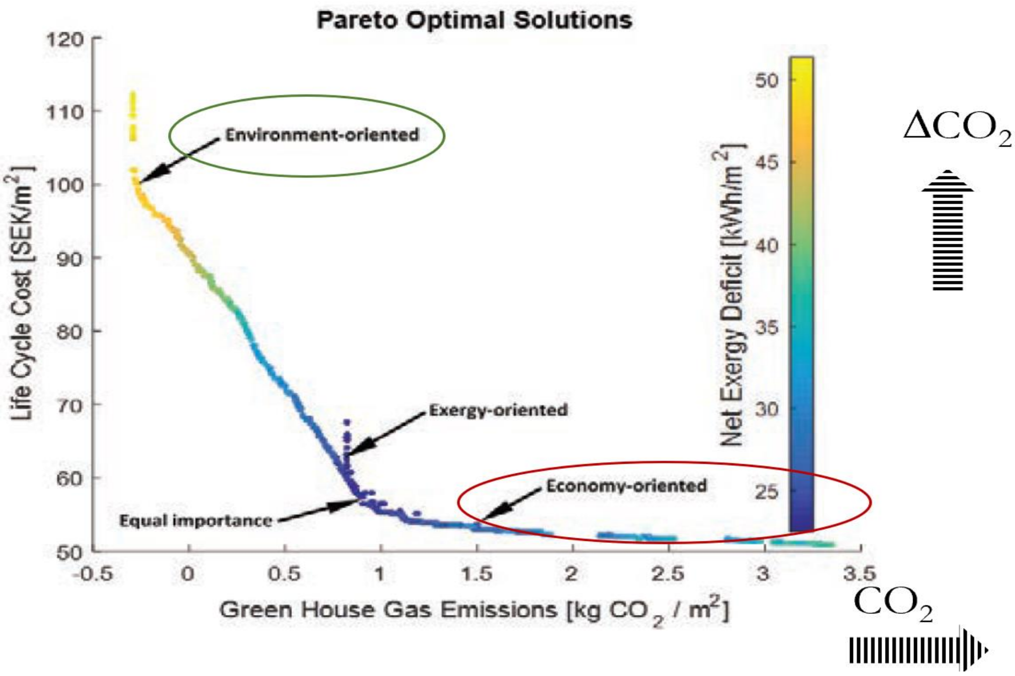

Figure 14. Pareto Optimality for Environment, Economy, and Exergy-Oriented Objectives [11].

On the other hand, the exergy-oriented solution of the authors gives about 2.4 kg CO_2/m^2 total emissions responsibility. This value is the lowest compared to economy and environment-oriented solutions, hinting that the second law may accommodate the Pareto principle.

4.2. Pareto in Heat Pumps

The unseen emissions responsibility according to the second law is given below.

$$\Delta CO_{2-1} = 2.1\times\left[\frac{0.95}{3.5}-\left(1-\frac{287.5\text{ K}}{333\text{ K}}\right)\right] = 0.283\text{ kg CO}_2\text{ / kW-h}_{\text{exergy}}$$

$$\Delta CO_{2-2} = 1.1\times\varepsilon_{des} = 1.1\times\left[\left(1\text{-}\frac{287.5\text{ K}}{333\text{ K}}\right)-\left(1-\frac{273\text{ K}}{293\text{ K}}\right)\right] = 0.075\text{ kg CO}_2\text{/kW-h}_{\text{exergy}}$$

$CO_{2\text{-}3}$= 0.567 kg CO_2/kW h_{exergy}

Emission responsibility of pumps used by the ground heat loop

$CO_{2\text{-}4}$ = 0.25 kg CO_2/kW h_{exergy}

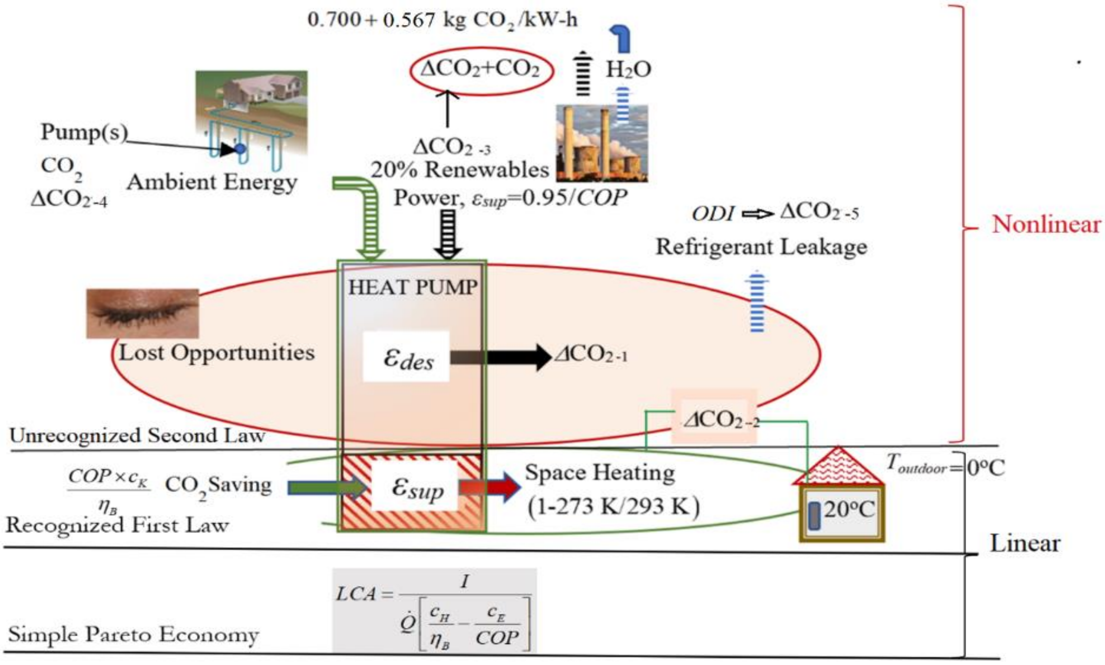

Figure 15. Environmental Footprint of a Heat Pump [4].

The total, 1.175, is only recognizable by the nonlinear second law of thermodynamics. The linear Pareto and the first law can only recognize the CO_2 at the power plant and pumps.

The heat pump is only rated with *LCA* and net CO_2 savings (at most) 3.5x0.35/0.85- 1.15- 0.15= 0.141 is saved but it is not that much: 0.141-1.175=-1.04. This result shows emission responsibility instead of any saving.

4.3. Pareto in Wind Energy

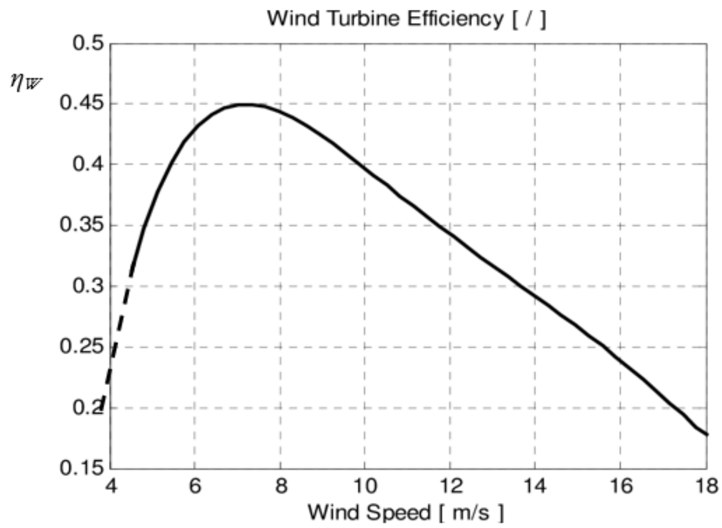

Figure 16. Typical Horizontal-Axis Wind Turbine Efficiency Change with Wind Speed [12].

$$\varepsilon_{pareto} = 0.21 = \left(1 - \frac{287.5}{T_{fw}}\right)$$

$T_{fw} = T_{fpareto} = 363.9$ K

Solve for the corresponding Pareto wind efficiency:

$$T_{fw} = 363.9 \text{ K} = \frac{284.15 \text{ K}}{\left(1 - 0.95 \times \eta_W\right)}, \; \eta_w = 0.22$$

From Fig. 16, the wind speed for the face value of Pareto is below four meters per second, less than the practical cut-in speed. Therefore, the Pareto economy cannot fully recognize wind energy.

4.4. Pareto in Geothermal Energy

$T_{fpareto}$ = 363.9 K (90.9ºC). This temperature may not render practical solutions in terms of power generation. For example, Fig. 17 shows a specific ORC power plant where the break-even temperature decides whether power generation or heat use has more value-adding potential (Unit exergy). For this case, the Pareto temperature is higher than the decision-making temperature of 340 K, meaning that Pareto does not permit power generation, which has high unit exergy of 0.95 kW h/kW h, compared to thermal exergy, until the ORC efficiency is increased from 0.115 to 0.145, to bring the break-even temperature to the Pareto temperature, which is technically difficult, even with additives to the working fluid (Fig. 18).

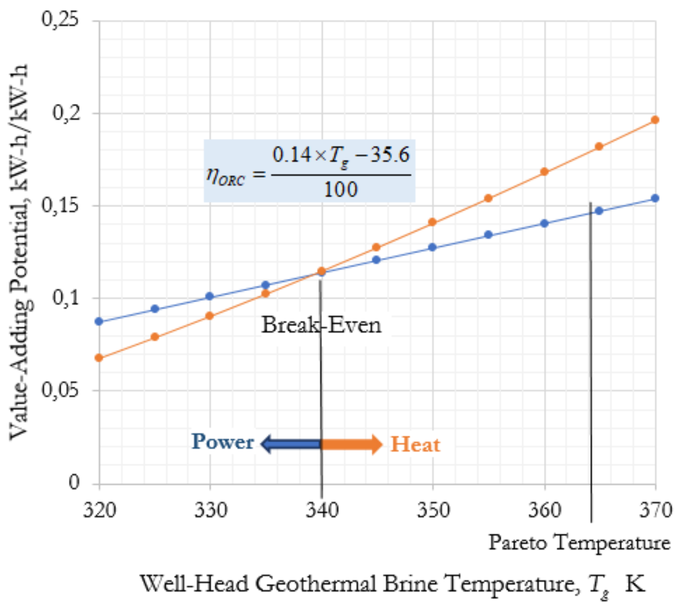

Figure 17. Break-Even Temperature of Value-Adding Potential in Terms of the Well-Head Temperature.

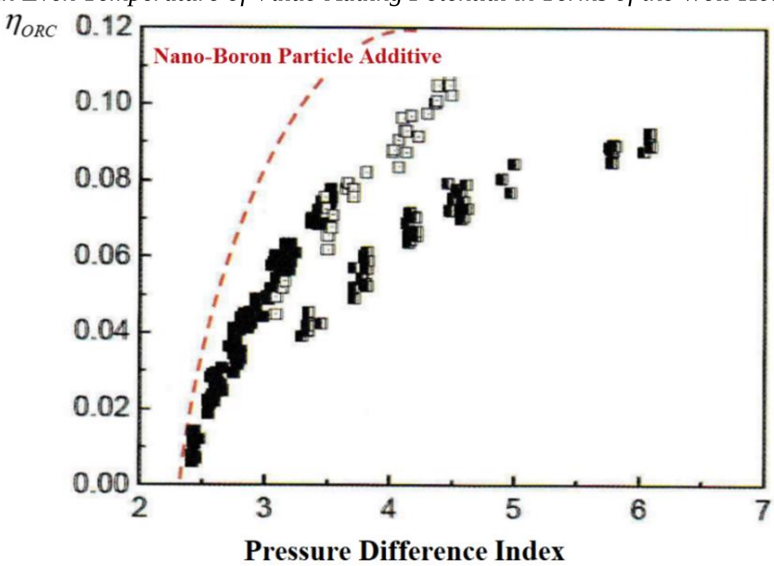

Figure 18. Improvement of ORC Efficiency with Boron Nano-Particle Additive [13].

4.5. Pareto and Concentrated PV Panel.

According to the simple Pareto economy, Fresnel lenses are very economical because they are cheaper than solar PV cells [14]. Fig. 18 shows a system. Assume that the area concentrating ratio, *CR* is equal to five. This value practically means that one-fifth of the original number of PV cells may be used while the PV panel temperature increases. Therefore, PV cells must be cooled to maintain the same efficiency by a cooling system that demands electrical power [15]. The equivalent concentration penalty, *p*, for this parasitic power demand must be considered. Eq. 20 is the simple economic analysis for the investment costs:

$$\text{Investment Cost Saving} = \left(\frac{1}{5+p}\right)c_{PV} - c_{FL} \tag{20}$$

Eq. 20 provides a break-even cost point for zero savings:

$$\frac{c_{FL}}{c_{PV}} < \left(\frac{1}{5+p}\right) = \left(\frac{1}{CR+0.2}\right) \tag{21}$$

For a given *p*-value of 0.2, the area concentration ratio of five is “economically” feasible, provided that the investment cost of the Fresnel lens, $c_{FL,}$ is less than (1/5.2) of the investment cost corresponding to the reduced size of the PV panel after adding the solar concentration feature. According to Eq. 21, there is no upper limit for *CR,* as long the constraint is satisfied in favor of cheaper Fresnel lenses. However, the imbalance between the solar thermal exergy gains due to the source temperature after concentration and the parasitic electrical exergy demand results in CO_2, and the system *CR* is limited according to the following analyses.

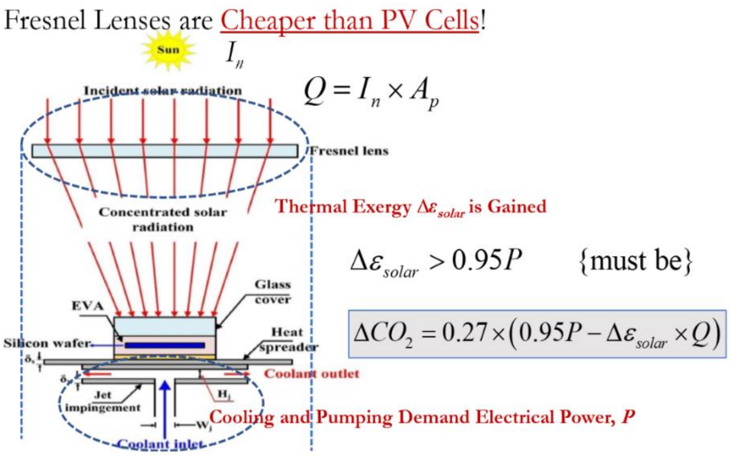

Figure 19. Simple Fresnel Lens Arrangement for Concentrated Photo-Voltaic System with Cooling [4].

The Exergy-Based Limit on *CR*

When the incoming solar irradiation over a given exposed area passes (like Fresnel lenses) or is reflected towards an absorber (like a parabolic concentrator), it is concentrated in a smaller area, and the temperature increases to T_{fC}. In contrast, the amount of solar irradiation remains the same. In other words, the solar energy remains the same (except for losses), but the exergy increases (useful work potential of the radiation).

If the area concentration ratio, *CR*, is sufficiently high (CR_{max}), then the unit solar exergy may theoretically reach the 0.95 kW h/kW h limit, then T_{fC} virtually increases to 5778 K.

$$CR_{\max} = \frac{0.95}{\varepsilon_{solar}} = \frac{TSI}{I_n} = \frac{1367.6}{I_n} \tag{22}$$

TSI is the total solar irradiation. If ε_{solar} is 0.556 kW h_{exergy}/kW h_{energy} (I_n = 800 W/m^2), then the exergy-based CR_{max} is 1.71. For I_n = 400, CR_{max} is 3.4. According to Eq. 1, at higher I_n values, CR_{max} is smaller (less necessary concentration). The unit exergy of 0.95 kW h/kW h may not be exceeded. Therefore, for the maximum theoretical PV efficiency η_{IPVth} of 86.8% for a stack of an infinite number of solar cells, using the incoming concentrated solar radiation, another theoretical limit on CR_{max} exists for the future:

$$CR_{\max} \leq \frac{\eta_{IPVth}}{\eta_{IPV}} \ \{Theoretical\} \tag{23}$$

For example, if η_{IPV} is 0.20: $CR_{\max} = \frac{0.868}{0.20} = 4.34$

Fig. 1 shows the CR_{max} versus I_n relationship for CR =1.25, 1.5, and 1.75. Therefore, any excess CR means exergy destruction. Higher the T_f, ΔT_f is closer to T_f. Also, note that:

$$\frac{\varepsilon_{solarc}}{\varepsilon_{solar}} = CR = \frac{\eta_{PVc}}{\eta_{PV}} \qquad \{if\ only\ power\ is\ generated\} \tag{24}$$

The efficiency of the PV panel increases with CR for ideally zero exergy destruction (all PV)

$$\frac{\varepsilon_{solarc}}{\varepsilon_{solar}} = \frac{1-\dfrac{T_{ref}}{T_f+\Delta T_f}}{1-\dfrac{T_{ref}}{T_f}} = CR \tag{25}$$

$$T_f = \frac{T_{ref}}{\left(1-\dfrac{0.95 I_n}{TSI}\right)}, \ Solving\ for\ \Delta T_f: \tag{26}$$

$$\Delta T_f = \frac{\left(1-\dfrac{1}{CR}\right)\times\left(T_f - T_{ref}\right)}{CR\left(\dfrac{1}{CR}-1+\dfrac{T_{ref}}{T_f}\right)} \qquad \{CR>1\} \tag{27}$$

From the denominator of Eq. 27, the non-negativity condition is obtained:

$$\frac{T_{ref}}{T_f} > 1-\frac{1}{CR} \tag{28}$$

Solving them simultaneously:

$$CR < \frac{TSI}{0.95 \times I_n} \tag{29}$$

For a maximum I_n of 1000 W/m^2, CR must be less than 1.44. Therefore, temperature peaking up to about 100 K may be achieved by applying the solar concentration technique at low PVT output temperatures. This is an alternative to PVT cascading, with less panel area requirement [3]. Fig. 2 shows the permissible design range of CR at a given T_f. For example, if T_f is 525 K (ε_{solar}=0.461 kW h_{exergy}/kW

h_{energy}), the maximum temperature lift, ΔT_f, is 260 K for CR = 1.5 and T_{ref} = 283 K. This temperature lift corresponds to the following rather modest unit exergy increase:

$$\Delta\varepsilon_{solar} = T_{ref}\left(\frac{1}{T_f} - \frac{1}{T_f + \Delta T_f}\right) \quad (30)$$

ε_{solar}=0.1785 kW h_{exergy}/kW h_{energy}. This is about a 38% increase in useful work potential. Fig. 3 shows the simultaneous solution of Eqs. 6 and 9 for CR = 1.5. These results show that CR rendering temperature lifts; thus, the unit exergy is quite limited compared to most literature [4]. Fig. 21 shows that in practice, the increase in the useful work potential of solar energy (exergy) does not exceed about 41% at I_n = 750 W/m^2. The Pareto economy cannot recognize any constraint on the CR_{max} with respect to the solar insolation, I_n.

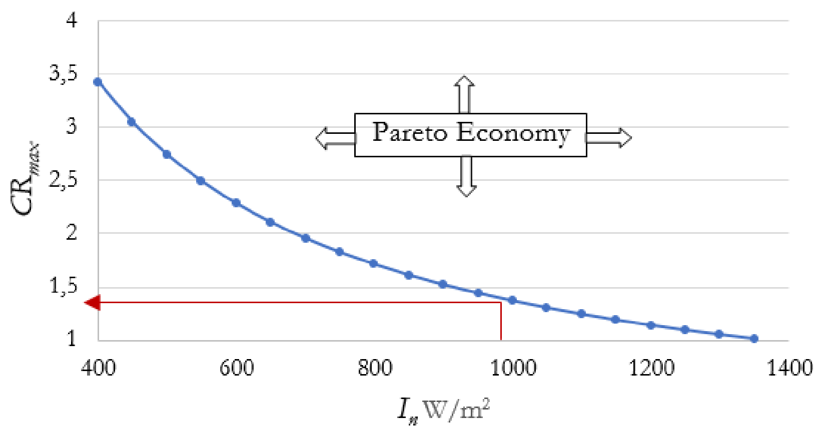

Figure 20. Variation of CRmax with In and the position of the Pareto Economy.

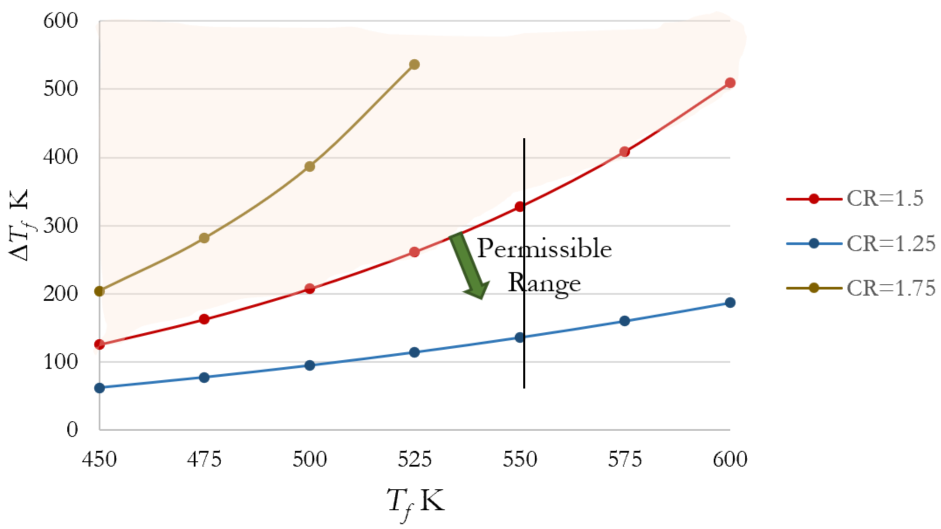

Figure 21. Temperature Peaking with Concentration Ratio, CR. Tref = 283 K.

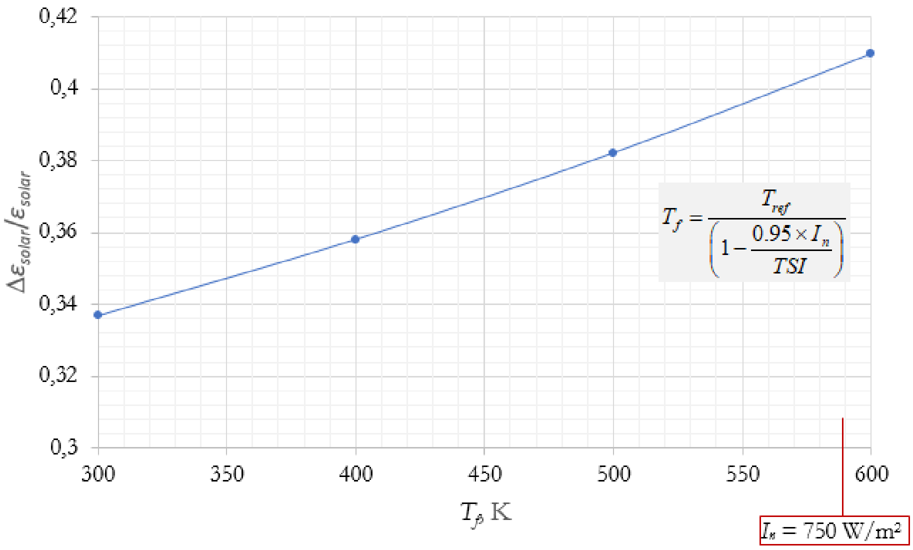

Figure 22. Unit Solar Exergy Lift with Tf. CR = 1.5.

5. DISCUSSION OF RESULTS

A new exergy-based, climate emergency-focused enviro-economic model was developed by decoupling the simple Pareto economy and then collapsing it into the new model in terms of the ideal Carnot cycle by a virtual Pareto Temperature. The new model distinguishes between direct emissions, recognized by the first law, and the nearly-avoidable emissions, recognized by the second law. Equivalent Pareto temperature is below the source temperature (real or virtual), T_f of many renewable applications. The comparison in Table 1 shows that the Pareto temperature is below the lower limits of practical applications, indicating that it may not rate energy systems sufficiently, except barely exceeding temperatures of geothermal ORC applications at low ΔT.

Table 1. Comparison of Pareto Temperature with Minimum Practical Virtual Temperatures.

Pareto Temperature: 360.9 K	Cases	
Minimum T_f of Cases	Solar PV	526.3 K
	Heat Pump	420.7 K (COP_{min}= 3)*
	Wind Turbine	463.7 K (η_{Wmin} = 0.40) See Eq. 9
	Geothermal Power with ORC	346.8 K (at low ORC ΔT)**
	Solar PV With Fresnel lenses	975 at CR = 1.5 (Fig. 21)

*$T_{fheat\ pump}$= T_{ref}/(1-0.95/COP). ** Use Eq. 9 with η_{ORCmax} = 0.18.

6. CONCLUSIONS

It may be argued that the new economic model needs to be compared with the literature, and the results must be compared. Reviewers usually require that it is necessary to compare the values obtained in the results section with the literature and state that it is necessary to support the conclusion with numerical values. As the literature section of this paper shows, the current linear economy and the new model are incompatible and may not be compared at all. This fact is underlined by the two references [1] and [2] in the literature survey section. Two laws of thermodynamics apply to two completely different aspects of energy, namely the quantity of energy (First law) and the quality (added value potential) of energy (second law). The simple economy usually provides a misleading result, especially for meeting the Paris agreement target on time. For example, Fig. 9 shows that only the new model can correctly predict the overall CO_2 emissions for a minimum value while the simple economy keeps being insensitive to the quality of energy (in this case, the source temperature). Therefore, a simple economy limits the CO_2 emissions problem to an emission trading schema (again, a cost item), which is obviously, way far from resolving the climate crisis due to human-caused global warming. Another forced comparison may be carried out in Fig. 20, where the Pareto economy tells us that and concentration ratio is economically admissible, whereas the new economic model shows that the solar concentrating ratio is limited to 1.4.

This paper concludes that a simple Pareto economy may not recognize one of the root causes of emissions. The new model offers a technique to accommodate the exergy-related emissions so that after identifying the root causes, new carbon mitigating methods and systems may be envisioned. These solutions should target minimum emissions due to exergy destructions. In this study, the simple Pareto principle was reduced and transformed into a virtual Pareto temperature and unit exergy to accommodate it in the new exergy-based, the two-dimensional economic model of the higher order. Results show that the economy and decision-making apparatuses must transform into this model to reach the Paris agreement.

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