Decarbonization: exergy to the rescue

BIROL KILKIS
Dr.
F-ASHRAE, Exceptional Service and Distinguished Service Awards ASHRAE
Science Encouragement Award, TUBİTAK, 1981
Country Manager, World Alliance for De-Centralized Energy
Professor Baskent University and Chair of Energy Engineering Graduate Program
Honored Member, America's Registry of Outstanding Professionals
Executive Committee Member EU ESTTP
TTMD and Polar Teknoloji, Ankara Turkey

Decoupling sustainable development from CO_2 emissions and global warming is the most urgent challenge of the World. While energy is required both in the forms of power and heat for sustainable growth and urbanization, CO_2 emissions follow a parallel trend with sustainable growth. i.e. CO_2 emissions continue to increase with sustainable development although 20+20+20 goals of EU are in place. These measures reduce the rate of increase in CO_2 emissions but cannot de-couple the relationship. This paper claims that exergy rationality may achieve the desired decoupling by following new recommended metrics for Decarbonization goals of the EU and gives a practical example of district heating with solar PVT panels.

1. Introduction

'We are paying for the quantity of energy but we are using only the quality (Exergy) of energy' – Prof.dr. Peter Novak[1]

The 20+20+20 goals of EU, namely 20% increase in energy savings, utilization of renewable energy sources, and efficiency, respectively each, may all reduce the CO_2 emissions rate but are not sufficient to reverse (decouple) the ongoing parallel trend with sustainable growth. In Eq. 1 and **Figure 1**, these three goals are supplemented hereby with a fourth goal, namely exergy rationality, expressed by the term ψ_R. This is the rational exergy management model (REMM) efficiency, which watches the balance between the quality of energy among supply and demand points in the built environment. In **Figure 1** HSDI is the Human (Sustainable) Development Index defined by UNDP and will replace HDI (Human Development Index) only if CO_2 emissions rate falls below the 1990 level. Eq. 1 shows that CO_2 emissions may be substantially reduced by increasing the exergy rationality, because there is a large window of opportunity between the current global ψ_R average of 0.20 and the practical bound that may exceed 0.70, without facing the dilemma of the diminishing returns, like the other goals of EU strategies face today.

It is clear that, if and only if, CO_2 emissions are reduced by increasing ψ_R by reorganizing human activities by exergy rationality to such a level that natural sinking mechanisms assisted by artificial capture of CO_2 emissions can take over and let CO_2 emissions go below 1990 levels. Eq. 3, and **Figure 2** show that exergy destructions must be minimum.

$$\sum CO_2 = \frac{RENEWABLES}{EFFICIENCY}(2-\psi R)\ SAVINGS \qquad (1)$$

$$\psi_R = \frac{\varepsilon_{dem}}{\varepsilon_{sup}} \quad \text{\{Exergy destroyed upstream\}} \qquad (2)$$

$$\psi_R = 1 - \frac{\sum \varepsilon_{des}}{\varepsilon_{sup}} \quad \text{\{Exergy destroyed downstream\}} \qquad (3)$$

1 Honorary Member of IIR, 2003, Fellow and Life Member of ASHRAE 1999; Honorary Member of REHVA, SITHOK and SLOSE.

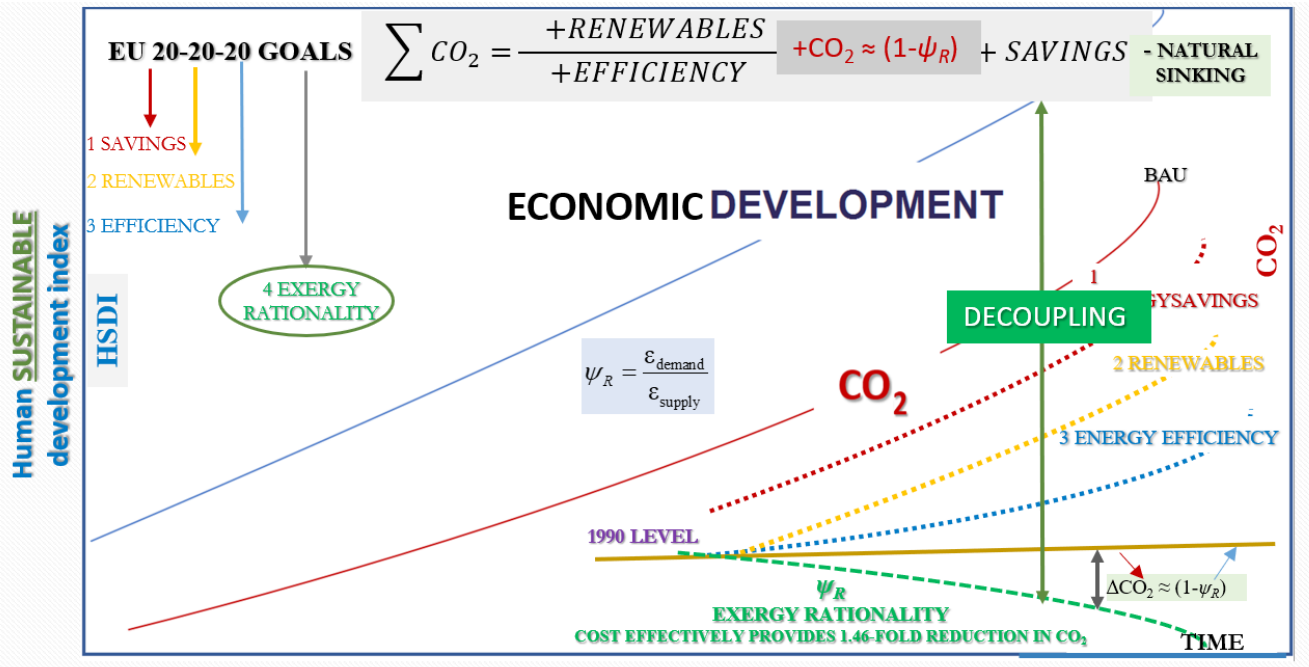

Figure 1. Phases of De-Coupling Between Emissions and Sustainable Development: Role of Exergy.

Here ε is the unit exergy (W/W) defined by the ideal Carnot cycle between two temperatures T_1 and T_2 of a process.

$$\varepsilon = \left(1 - \frac{T_1}{T_2}\right) \quad (4)$$

Current EU strategies about electrification of heating and cooling with heat pumps do not make much sense for the Second-Law of Thermodynamics: a natural gas-fired thermal power plant burns natural gas at T_f= 2200 K and electricity is used by a heat pump with a *COP* of 3 for radiant floor heating at supply and return temperatures of 330 K and 320 K, respectively. Then, exergy-based *COP*, namely *COPEX* is less than one due to large exergy destructions (See **Figure 2**) and ψ_R, which is responsible for CO_2 emissions is quite small. For an exergy-rational system (*COPEX*→1) *COP* must approach to 28.7, which is unpractical today. 283 K is the reference temperature, T_{ref}.

$$\psi_R = \frac{1-320/330)}{(1-283/2200))} = 0.035 \quad \{\text{See Equation 2}\}$$

$$COPEX = COP \cdot \psi_R = 3 \times 0.035 = 0.105 \quad (5)$$

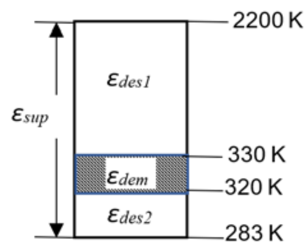

Figure 2. Exergy Flow Diagram (Eq. 2).

2. Justification of the Study

Today's limited ability to cope with the real issues that affect sustainability, global warming, and energy security, originates from the fact that all energy projections, model studies, carbon emission predictions, and mitigation calculations, international protocols, and energy system designs are based only on the quantity of energy efficiency, leaving the root cause beyond touch. In fact, thermodynamic irreversibility that impacts harmful emissions with the end result of global warming lies within the new scope of rational exergy management, which deals with the **quality** of energy resources and the quality of energy required for different applications in the built environment. With current systems, which largely count on fossil fuels, there is an unbalance among them, that compounds energy spending and harmful emissions because the opportunities of fully utilizing the quality of energy resources are missed. A simple exergy input and output type of exergy balance, similar to the energy balance cannot provide the scale of the unbalances taking place today at large either. **Figure 2** is the fundamental tool shown above to find the missing piece of the puzzle and establish the missing link. A key definition and a new methodology are necessary to bring all the energy supply, demand, and environmental issues and parameters on a common platform with a unified metric of rational allocation of energy resources in both quality and quantity. This is especially essential with the diversification, hybridization, and systems approach of the EU along with the increasing share of renewable energy resources, smart cities, and low-energy and low-exergy buildings (Sustainable and green buildings). All EU Directives, being issued so far are based however on the First-Law, which recognizes only the quantity of energy. In fact, every energy resource has a different quality, named exergy, which is the amount of useful work that can add value to the society and to the built environment at large, if utilized properly from a given amount of energy of a given type and quality. According to the Second-Law, it is important to use the right quality of energy at the right balance of quality demand at a given application, at the right time, and at the right order in addition to the right quantity (energy). Therefore, it is crucial to establish also a quality balance among different sources of energy having different exergy and different energy demand points at different exergy. This requires a new exergy allocation methodology and re-wiring of energy sources among all energy demand points. Even the forms and quantity of energy sources are balanced, with the demand points, remaining exergy imbalances cause exergy destructions, which are responsible for additional energy demand and additional – but avoidable – CO_2 emissions, which are all invisible to the First-Law. Rational Energy Management Model [1] is the potentially key rescue mission to global warming and decoupling issues. Sustainable buildings of today are thermodynamically interconnected to the built environment, because buildings generate, share, and consume energy with all elements of the built environment, which also need to be sustainable. Such a level of interconnection along with the hybridized utilization of renewable energy sources, including reject heat of different types, temperatures, and exergy also makes it necessary to acknowledge and identify the existence of different sources and demands of exergy in different forms, temperatures, and locations. This further necessitates a holistic approach.

3. EU Literature

The only European initiative about the inclusion of exergy in EU energy analyses is published by Science Europe [2]. In appreciation and thanks to the motivation and insight into the subject matter by the Authors of this important publication, namely Dr. Paul Brockway, University of Leeds, Professor Jo Dewulf, University of Gent, Professor Signe Kjelstrup, Norwegian University of Science and Technology, Professor Susanne Siebentritt, University of Luxembourg, Professor Antonio Valero, CIRCE, Research Centre for Energy Resources and Consumption, University of Zaragoza, Dr. Caroline Whelan, Science Europe, their following statement is hereby repealed. In quote:

'Educators, researchers, policymakers, stakeholders, and citizens are urged to consider energy and natural resources on the basis of exergy, and in doing so understand that:

- *exergy measures energy and resource quality;*
- *exergy-destruction foot-printing improves industrial efficiency;*
- *exergy offers a common international energy-efficiency metric;*
- *optimal use of our limited mineral resources can be achieved by the application of exergy rarity;*
- *and exergy should be integrated into policy, law and everyday practice.'*

4. Transformation of Non-Thermal Renewables

Mechanical energy, E of all types like the kinetic energy of flow, the potential energy of stored water of mass, m and specific heat, C_p may be mapped into the Carnot-cycle temperature field by a virtual source temperature, T_f by using the equivalency of energy and heat by Kilkis [2]. This relationship reduces to the following expressions for solar and wind energies, respectively.

$$\frac{I_n}{1366} = \frac{\left(1-\frac{T_{ref}}{T_f}\right)}{\left(1-\frac{T_{ref}}{5778K}\right)} \quad (6)$$

$$T_f = \frac{T_{ref}}{(1-\eta_w)} \quad (7)$$

η_w is the efficiency of the wind turbine. 1366 W/m² is the solar constant.

5. CO_2 Emissions and Exergy Rationality

The compound CO_2 emissions, including the effect of exergy destruction, is given in Equation 8.

$$\sum CO_2 = \left[\frac{c_l}{\eta_l} + \frac{c_m}{\eta_m \eta_T}(1-\psi_R)\right] Q_H + \frac{c_m}{\eta_m \eta_T} E \qquad (8)$$

This Equation, which is derived from the Rational Exergy Management Model (REMM), establishes the environment metric. If renewable energy sources are the primary energy source and power is also generated, then the first and the last terms drop.

The following expression, namely *EDR* is the *Ratio of Emissions Difference*, which must be close to one.

$$EDR = 1 - \left[\frac{CO_2}{CO_{2\ base}}\right] \qquad (9)$$

The term $CO_{2\ base}$, which is 0.63 kg CO_2/kW-h is the standardized emission rate calculated with practical defaults for 0.5 kW-h thermal and 0.5 kW-h electrical loads per hour. *c* values are based on natural gas (0.2 kg CO_2/kW-h, 0.85 is the typical boiler efficiency, and 0.35 is power generation and transmission efficiency. The current global average of ψ_R is taken to be 0.2.

6. Recommendations

Above review reveals that the Second-Law provides further insight and ability to further decarbonize EU and the globe in a more realistic and effective way, beyond the point where the First-Law stops. The key parameter, namely the ψ_R is a derivation from the Carnot Cycle in terms of supply and demand exergies. Thus, a simple transformation of all EU directives is possible by applying the factor ψ_R, which is shown in **Table 1**. For cold processes where the temperatures are below T_{ref}, the term (T_{ref}/T_s) in all equations are inverted.

Table 1. Sample Transfer Functions for EU Directives.

EU Terms (Sample)	First-Law Definition	Second-Law	Comments
Performance coefficient	*COP*	COP_{EX}	Multiply *COP* by ψ_R.
Primary Energy Ratio	*PER*	*PEXR*	(Inverse of *PEF*) Multiply *PER* by ψ_R.
Primary Energy Factor	*PEF*	*PEFX*	Divide *PEF* by ψ_R. Apply to electrical and thermal power separately.
Primary Energy Savings	*PES*	PES_{EX}	Cogeneration applications. Eq. 14.
Tonne oil equivalent	*Mtoe*	*MtoEX*	Multiply Mtoe by ψ_{RF}.

Exergy-Based PER (Inverse of PEF)

$$PER = \frac{Q_S}{Q_f / (\eta_{ITH} \cdot COP)} \qquad (10)$$

$$PEXR = \frac{E_{Xs}}{E_{Xf} / \eta_{ITH}} = \frac{\varepsilon_s \cdot Q_s}{\varepsilon_f \cdot \frac{Q_s}{(\eta_{ITH} \cdot COP)}} = \frac{\left(1-\frac{T_{ref}}{T_s}\right)}{\left(1-\frac{T_{ref}}{T_f}\right)} \cdot (\eta_{ITH} \cdot COP) = \psi_R \cdot PER$$

{From fuel input at the plant to the point of use} (11)

$$PEXR = \eta_{ITH} \times COP_{EX} \qquad (12)$$

Exergy-Based PEF

$$PEFX = \left(\frac{1}{\psi_R}\right) \cdot PEF \qquad (13)$$

Because the exergy of electric power and thermal power at different temperatures and enthalpy have a great difference, *PEF* and *PEFX* need to be broken down to thermal and electric power separately.

Exergy-Based PES (For co-generation)

$$PES_{EX} = \left(1 - \frac{1}{\left[\frac{CHPE\eta}{\mathrm{Re}fE\eta} + \frac{CHPH\eta}{REFH\eta}\right] \times \left(\frac{2-\psi_{R\,ref}}{2-\psi_R}\right)}\right) \times 100 \qquad (14)$$

Exergy-Based Mtoe

$$MtoEX = \frac{\left(1-\frac{T_{ref}}{T_s}\right)}{0.881} \times Mtoe = \psi_{RF} \times Mtoe \qquad (15)$$

Here, ψ_R is indexed to the unit exergy of crude oil, ε_F, namely 0.881 W/W.

From the exergy point of view, it has been shown above in terms of *PEXR* that once the electrical power is generated- even from solar or wind- it must stay as electrical power instead of converting it to thermal power unless the average *COP* value of heat pumps in heating reach beyond a value of 8. This also shows that one needs a common base by converting exergy to cost or vice versa. In this respect, the cost of exergy destruction per unit supply exergy may be embedded into cost equations, like life cycle cost analysis optimizations. *c* is the unit cost.

$$\Delta C_{EX} = c_{EX} \frac{\sum \varepsilon_{des}}{\varepsilon_{\sup}} \quad (16)$$

7. Case Study

A solar PVT plant serves a 4DE district energy system. Power is partially used to drive the circulation pumps in the district. The rest of the generated power is distributed in the grid for electrical demand of different types and purposes, including mass transit. Hot water is distributed by a system of pipelines in the district. This heat may be converted to cold by individual absorption and or adsorption units on site of customers, on demand. **Figure 3** shows the basics of the system. The common mistake in the design and operation of such systems is the ignorance of the unit exergy difference between electrical and thermal powers. Among all ancillaries, which demand power circulation pumps need to be carefully optimized such that thermal exergy provided to the district must exceed electric power exergy demand of the pumps, ignoring other parasitic losses and ancillary demand.

$$E_{XH} > E_{XP}(D, L) \quad (17)$$

Here E_{XP} is a function of the pipe diameter, D and the one-way distance of the loop between the PVT plant and the district, L. For the limiting case of Equation 15 and the given installed capacity, C of the PVT plant, providing heat to the district between 330 K and 320 K, feeding radiant panel heating and at the same time providing in a parallel piping heat at 340°C for DHW and to avoid Legionella risk in open systems, like showers and faucets. Thus, the overall exergy supply to the district takes place between 340°C and 320°C:

$$E_{XH} = C\left(1 - \frac{320}{340}\right) = 0.059C$$

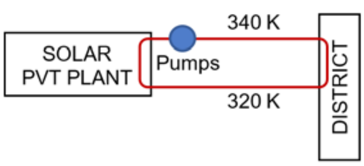

Figure 3. District Energy System with Solar PVT Plant.

If for example, the power demand of the installed pump stations, P_s is 15% of the thermal capacity, C, COP of the district energy system between the plant supply and district demand points looks quite favourable:

$$COP = \frac{C}{P_s} = \frac{C}{0.15C} = 6.7$$

But $COPEX$ tells a different story:

$$COPEX = \frac{0.059C[\mathrm{W/W}]}{0.15\mathrm{C}[1\mathrm{W/W}]} = 0.39$$

1 W/W is the unit exergy of electricity. From Equation 5, ψ_R is 0.058 and the corresponding CO_2 emissions responsibility (Although Solar Energy is the Primary Source) may be calculated from Equation 9. In order to improve the exergy performance of the system pipe diameter may be increased, which affects the Reynolds number but at the same time the flow speed in terms of the flow rate and the inner pipe cross-sectional area. A larger but optimal pipe diameter may be determined but Reynolds Number, Re must be above a certain limit for turbulent flow and the increase in the embodied energy, exergy, and cost corresponding to the pipe diameter increase must be balanced by the cost of electricity generation and operating exergy. The maximum L, namely L_{max} is related to exergy.

$$L_{\max} < \frac{E_{XH}}{\Delta P_S(1)} \quad (18)$$

Therefore, the distance from the plant to the district is a function of the supply and pump demand exergy. Piping material is also important.

Electric power is in DC in order to avoid inverters and re-conversion to DC in some household equipment like TV screens, LED lighting, and computers.

8. Conclusions

The study presented in this paper shows the need to approach the Second-Law of Thermodynamics if EU wishes sincerely to pursue decarbonization further with all fairness to all stakeholders. Such a move will also become a role model for all other countries of the World. In quantified terms, the task is not of a paramount magnitude. Instead, **Table 1** shows that a single key term, namely ψ_R shall transform all directives and rules in a simple fashion with a new mindset and perspective towards the exploitation, generation, transformation, and utilization of our limited energy resources for a truly sustainable future that we all envision.

We should use;

- The right quality of energy,
- At the right application,
- At the right order of utilization,
- At the right time and,
- At the right location.

In conclusion, what EU needs is a strong willingness, motivation, mobilization of the stake-holders and mindset to accomplish such a monumental task with minimal effort with minimal transformation, simply by using a few key parameters. Such a move will especially be useful and effective in the decoupling process for new 4DE systems.

Furthermore, solar energy plants need to be optimally hybridized by other renewables, including district waste for biogas, with support from fossil fuels if necessary [3,4]. In order to improve *COP* and *COPEX*, Low-Exergy Buildings must be designed and installed along with high-efficiency pumps and electric motors need to be utilized [6]. ■

9. Nomenclature

A_d	Pipe inside the cross-sectional area, m^2
c	Unit emissions factor, $kgCO_2$/kW-h
c_{EX}	Unit cost of exergy destruction Euro/kW-h
C	Thermal plant capacity, kW or MW
$CHPE\eta$	Partial power generation efficiency
$CHPH\eta$	Partial heat generation efficiency
CO_2	Carbon dioxide emission, kg CO_2
COP	Coefficient of Performance
COPEX	Exergy-Based Coefficient of Performance
E	Electrical energy (load), kW-h
EDR	Ratio of carbon CO_2 emissions difference to the base emission, dimensionless
E_x	Exergy, kW or kW-h
I_n	Net solar insolation normal to PVT, /m^2
L_{max}	Maximum district piping distance (one way), km or m
Mtoe	Megaton of oil equivalent
MtoEX	Exergy embodied Megaton of oil equivalent
PEF	Primary energy factor
PEFX	Exergy embodied primary energy factor
PER	Primary energy ratio
PES	Primary energy savings ratio
PES_{EX}	Exergy embodied primary energy savings ratio
PEXR	Exergy-based primary energy ratio
Q, Q_H	Thermal energy (load), kW-h
$RefE\eta$	Reference power generation efficiency
$RefH\eta$	Reference heat generation efficiency
T	Temperature, K
V	Volumetric Flow, m^2/h
L	One-way Circuit Length, km
P	Pressure, Pa
P_s	Power demand for pump stations, kW
ΔP_s	Power demand for pump stations per kilometer of the pipe circuit in the district, kW
D	District Pipe Inner Diameter, m
Re	Reynolds Number

Greek Symbols

η_{EX}	Second-law efficiency, dimensionless
η_T	Power transmission and distribution efficiency
ψ_R	Rational exergy management efficiency
ε	Unit exergy, kW/kW
η_I	First-Law Efficiency
η_{II}	Second-Law Efficiency
μ	Dynamic Viscosity, kg/m-s
ΔC_{EX}	Cost of exergy destuctio, Euro

Acronyms

CHP	Combined Heat and Power
DHW	Domestic hot water
DC	Direct current
4DE	Fourth-Generation district energy system
EU	European Union
HDI	Human Development Index
HSDI	Human Sustainable Development Index
Mtoe	Megaton of oil equivalent (According to the First-Law)
MtoEX	Megaton of oil equivalent exergy (According to the Second- Law)
PVT	Photo-voltaic-thermal
REMM	Rational Exergy Management Model
UNDP	United Nations Development Program

Subscripts

base	Base
dem	Demand
des	Destroyed
E	Electric
f	Resource temperature, or Adiabatic Flame Temperature (Real or virtual), K
F	Crude oil
H	Thermal (Heat)
in, out	Inlet and outlet connections of a hydronic circuit
l, m	Local power plant, distant power plant, respectively
min, max	Minimum, maximum
ref	Reference
sup, ret	Supply, Return
s	solar
o, ref	Reference
p	Pump
T	Power transmission
w	Wind
X, EX	Exergy, exergetic

10. References

[1] Kılkış, S. 2011. A Rational Exergy Management Model to Curb CO_2 Emissions in the Exergy- Aware Built Environments of the Future, Doctoral Thesis, Division of Building Technology School of Architecture and the Built Environment, KTH Royal Institute of Technology, Stockholm, Sweden.

[2] Kılkış, B. ve Kılkış, Şiir. 2015. Yenilenebilir Enerji Kaynakları ile Birleşik Isı ve Güç Üretimi (Combined Heat and Power Generation with Renewable Energy Resources) *TTMD*, Pub. No: 32, First Ed., ISBN: 978-975-6263-25-9, 371 pages, Doğa Pub. Co., İstanbul, 2015.

[3] Kilkis, B., Kilkis, Siir, Kilkis, San. 2017. Optimum Hybridization of Wind Turbines, Heat Pumps, and Thermal Energy Storage Systems for Near Zero-Exergy Buildings (NZEXB) Using Rational Exergy Management Model, Paper No. 2, 12th IEA Heat Pump Conference, 15-18 May, Rotterdam 2017. Papers online, https://www.eiseverywhere.com/ehome/index.php?eventid=165152&tabid=558494 Also, abstracted in print, pp: 179-180.

[4] Kılkış, B. and Kılkış, Şiir. 2017. New Exergy Metrics for Energy, Environment, and Economy Nexus and Optimum Design Model for Nearly-Zero Exergy Airport (NZEXAP) Systems, *Energy (2017)*, doi: 10.1016/j.energy.2017.04.129.

[5] Kılkış, Şiir. 2012. A net-zero building application and its role in exergy-aware local energy strategies for sustainability, *Energy Conversion and Management* 63: 208–217 · November 2012. doi:10.1016/j.enconman. 2012.02.029, *Energy J*.

[6] Kilkis, B. and Kilkis, San. 2014. Energy and Exergy Based Comparison of Utilizing Waste Heat of a Cogeneration System for Comfort Cooling Using ORC Driven Chillers or Heat Pumps Versus Absorption/Adsorption Cycles, ASME ORC 2013, Conference Proceedings, 7-8 October, De Doelen, Rotterdam, the Netherlands.