Targeting Nearly-Zero Exergy Hospital Buildings (nZEXHB): a new performance metric and a case study

BIROL KILKIS
Prof. Dr., Fellow ASHRAE
Baskent University, Energy Eng.
Program Chair and TTMD President
Ankara, Turkey
birolkilkis@hotmail.com

Hospitals are the most energy-intensive buildings [1, 2]. Yet, for true decarbonization in the EU countries, all future buildings, including hospitals, must be exergy-rational in addition to be energy efficient, because CO_2 emissions are linearly proportional to both conditions [3]. In this context, a new definition, namely nZEXHB and its fundamental theory with a rating model, is introduced and explained with a short case study using the Rational Exergy Management Model (REMM). EU Decarbonization instruments are also re-visited from the exergy point of view.

Keywords: near-zero buildings, exergy-rational hospitals, Rational Exergy Management Model, decarbonization, nearly-zero-exergy hospital building (nZEXHB)

Exergy or Energy?

> "We pay for the quantity of energy but we only use its exergy (Quality of energy)"
>
> – 2004, Peter Novak, ASHRAE TC 7.4

This sad fact is exemplified in **Figure 1**, which shows the energy flow of a ground-source heat pump used in a hospital building. The electric power input to GSHP is utilized to supply heat with a given First-Law *COP* at given operating conditions. But the input side and the supply side have different exergy levels.

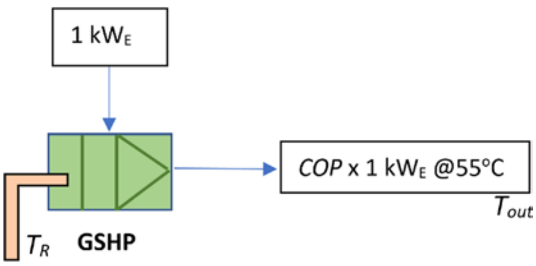

Figure 1. Exergy input and output for GSHP.

The First-Law of Thermodynamics cannot distinguish this difference. From an exergy point of view, the *COP* of the GSHP needs to be at least equal to 7.28 if the input and output exergies must be even. By considering the ideal Carnot Cycle (Temperature Factor) of the heat supplied by the GSHP at 55°C, and taking the unit exergy of electric power to be unity:

$$COP_{min} = \frac{1}{\left(1 - \frac{283\text{K}}{(55+273)\text{K}}\right)} = 7.28 \quad (1)$$

nZEXHB Building

In the quest of reaching the goals of the recent Paris Agreement for reducing CO_2 emissions, net-zero energy buildings (NZEB) and net positive-energy (NPEB) buildings are becoming common [5]. Following the foot-steps of the above argument shown in **Figure 1**, although general definitions for NZEB have been published, there are other issues to be resolved [6]. A major issue that has not been addressed yet in the building and energy sector is the fact that, with the increasing share of renewable energy resources and systems in the built environment at different exergy levels, their exergy differences and the need for exergy balance between the supply (resource) and the demand points (built environment, such as buildings) need to be identified as well as their importance in optimum and net-positive solutions have to be acknowledged [6]. Almost all of the literature is concerned with the First-Law of Thermodynamics, which is not sufficient to address these problems. Therefore, the Second-Law needs to be incorporated in all related analyses, design, and operation phases. Current practice is primarily focused on the exchange of electrical energy only, which has a unit exergy of almost 1 so that exergy exchange of electricity is almost identical to its energy exchange, except quality of the currents, for example PV generated and thermal power plant generated. In contrary, Thermal energy at different states and temperatures mean a wide variation of the thermal energy quality (exergy). Exergy differences between the supply and demand points yield irreversible exergy destructions and, thus, avoidable but important amounts of CO_2 emissions. Today, Denmark is the only EU country that factors-in the thermal energy exchange. In order to better assess the environmental performance of buildings, in particular, hospitals a new definition has been proposed to ASHRAE TC 1.6 Terminology:

nZEXHB: Nearly-zero Exergy Hospital Building is an individual building or compound connected in a district, which on an annual average basis satisfies at least 70% of its total exergy of heat and power [7].

Such a hospital building faces the challenge of a quadrilemma among Environment, Energy, Exergy, Economy, and Safety and Health, which is shown in **Figure 2**. While nZEXHB satisfies the 80% Law, it must also optimally satisfy all four elements of this quadrilemma without much sacrifice. This is possible on an exergy platform.

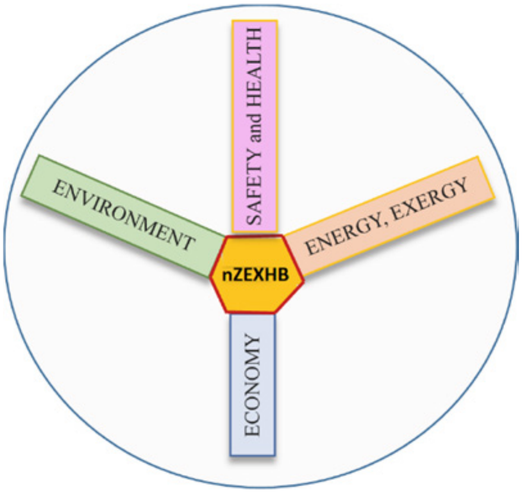

Figure 2. Quadrilemma of nZEXHB.

Rational Exergy Management Model

The so-called exergy platform may be established by using the Rational Exergy Management Model (REMM) [3]. This Model defines a rational exergy management efficiency, namely ψ_R. It checks the balance between the supply and demand exergy, thus the amount of exergy destroyed. It depends on where the major exergy destruction occurs: upstream or downstream of the exergy flow in a process:

$$\psi_R = \frac{\varepsilon_{dem}}{\varepsilon_{sup}} \quad \text{\{If exergy is destroyed upstream\}} \quad (2)$$

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

Here, ε is the unit exergy defined in terms of the ideal Carnot Cycle:

$$\varepsilon = \left(1 - \frac{T_{ref}}{T}\right) \quad (4)$$

T_{ref} is the environment reference temperature. Many hospitals use GSHP and therefore it may be taken to be the average ground temperature like 283 K. T is the application (or source) temperature. For non-thermal sources like solar insolation (electro- magnetic) and wind energy (mechanical), a virtual, Carnot Cycle-based source temperature is calculated [7]. For example, for solar energy with an insolation, I:

$$T_s = \frac{T_{ref}}{1 - 6.96\times10^{-4} \times I} \quad (5)$$

Finally,

$$E_x = \varepsilon \times Q \qquad \{Q\text{: Energy, } E_x\text{: Exergy}\} \quad (6)$$

Exergy-Based Evaluation Model

In this model, four renewable sources of input exergy are identified, namely biogas (*BG*), Ground Heat (*G*), Building integrated PV (*BIPV*), and Waste heat (*W*). A small amount of wind energy is embedded to BIPV slot, because on-site wind turbines may generate uncomfortable noise to patients and medical personnel and even may generate enough electro-magnetic field to affect medical instruments. BIPV is chosen because, façade mounted BIPV emf effect may be reduced by water circulation behind them, which at the same time generates hot water in summer months, while cooling the PV cells for a steady efficiency. The outline of the model is shown in **Figure 3**. In this Figure, c is the CHP capacity chosen with respect to the peak power load and X is the portion of the power output of CHP to the GSHP.

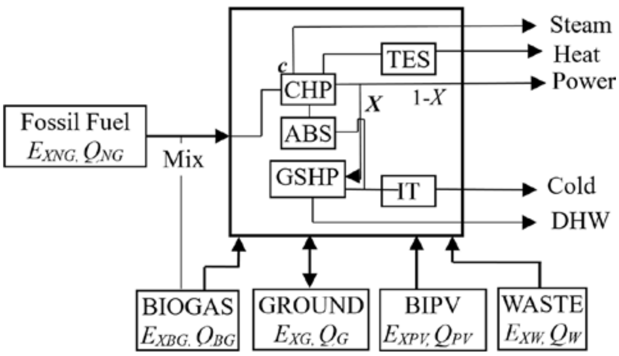

Figure 3. Optimization base model for nZEXHB.

By choosing the c close to one means the CHP plant will be redundant for several hours per year. In contrary, if c is chosen too low, then the fossil fuel portion of the mix will increase such that nZEXHB criteria will not be satisfied. By varying the portion of the power generated by the CHP system, X given to the GSHP system effects the objective function, because it indirectly changes the design c value.

The annual objective function OF_a for nZEXHB is a function of the above renewable sources and the fossil fuel mix (*NG*).

$$OF_a = \frac{OF_W \times HDH + OF_S \times CDH}{(HDH + CDH)} > 0.70 \quad (7)$$

Here, *HDH* and *CDH* are the heating and cooling degree hours, respectively. Equation 8 apply for both winter and summer conditions but the results will be different.

$$OF_W = OF_s = \frac{E_{XBG} + E_{XG} + E_{XPV} + E_{XW}}{E_{XNG} + E_{XBG} + E_{XG} + E_{XPV} + E_{XW}} \quad (8)$$

The following constraints apply due to physical and environmental limitations:

$$E_{XG} \le E_{Xgmax} \quad (9)$$

$$E_{XPV} \le E_{XPV} \quad (10)$$

$$E_{XBG} \le E_{XBG} \quad (11)$$

Case Study

A concept study was carried out in order to investigate the potentials and means of retrofitting the Turgut Özal hospital in the city of Malatya in Turkey.

Figure 4. 900-Bed Turgut Özal Hospital.

The hospital used to be heated by steam boilers running on natural gas and cooled by electric (grid) chillers. The operating costs soared up to 20% almost and a retrofit project was requested. Obviously the OF_a was zero and ψ_R was around 0.18. A complete survey revealed potential exergy intakes from on-site biogas from plumbing wastes, solar PV, ground heat (pump), and waste heat. **Table 1** gives the potential Exergy inputs identified for the terminal buildings without major retrofitting. PV modules on the roofs are quite limited both due to roof area and more importantly due to FAA (Federal Aviation Administration) restrictions to avoid glare and electromagnetic interference with avionics of the planes landing and taking off from a nearby airport. Instead, building integrated PVTC modules are envisioned on suitable vertical building walls. A PCTC module is a combination of PV and TEG modules on each site of the wall and part of the electrical energy activated-TEG modules either for sensible radiant panel cooling or heating by a simple switch of the DC current polarity. **Figure 5** shows the so called the solar brick wall. On site wind turbines are not envisioned due to sound pollution.

Once the *c* and *X* values were optimized independently from economical points of view [8], the fuel mix was optimized along with Equations 8-a and 8-b by varying the natural gas to biogas mix ratio, *m*. The variation is shown in **Figure 6**. Here, OF_a reaches to a peak of about 0.76 when *m* is 6.

At this optimum point, OF_a thus satisfies the 0.7 condition, which means that the hospital may reach nZEXHB status. OF_a in fact has a close relationship with ψ_R too. The overall value was calculated for the design for various arrangements and its impact on OF_a was investigated. Results are shown in **Figure 6**.

According to **Figure 7**, the retrofit is successful both in satisfying the $OF_a > 0.7$ condition and the $\psi_R > 0.7$ condition. This result shows that by satisfying the ψ_R condition, OF_a condition may also be satisfied, because they are both related to exergy rationality.

Table 1. Model inputs [7] (See Equation 6 for E_x).

Exergy Intake	Q, MW_h (thermal) Low Case	Q, MW_h (thermal) High Case	*T*, K	*ε*, W/W	E_x, MW (Thermal except PV systems) Low Case	E_x, MW (Thermal except PV systems) High Case
Natural Gas, *NG*	3.42	1.93	2200	0.87[b]	2.97	1.68
Biogas, *BG*	1.14	2.63	2200	0.87	0.99	2.28
NG + BG	4.56	4.56			3.96	3.96
Ground Heat, *G*	0.876	2.00	293	0.034	0.030	0.068
Solar, *PV* (All derivatives)	na		na	1	3.55 (electric)	
Waste, *W*	1.5		293	0.034	0.051	

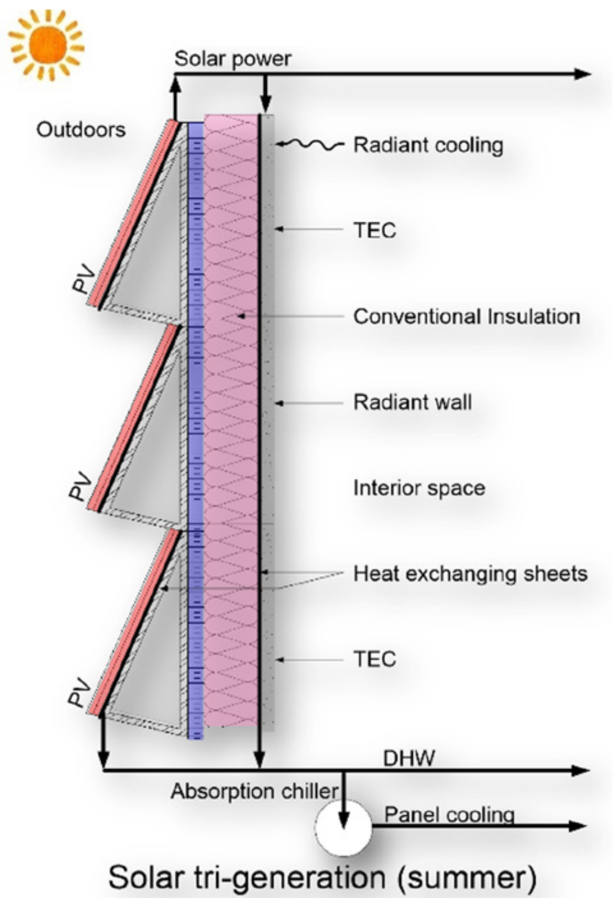

Figure 5. Solar Brick Wall layout.

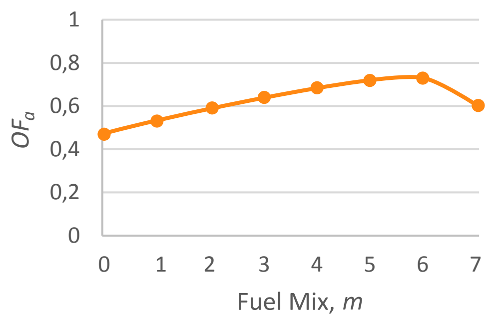

Figure 6. Variation of OF_a with fuel mix, m. [8].

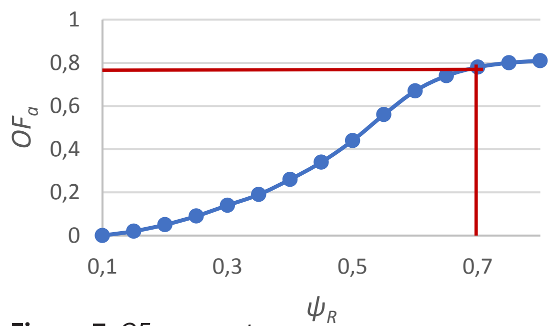

Figure 7. OF_a versus ψ_R.

These results were achieved by optimizing the electromechanical system. **Figure 8** shows the system design for Winter operation. In summer absorption chillers utilize the excess heat of the CHP unit and GSHP delivers cold.

Contributions to Decarbonization Efforts of the EU: A Revisit

EU is striving to decarbonize the member countries by using the First Law only. On the other hand, EU is trying to electrify the heating and cooling sector by using heat pumps. In this paper, it has been shown in **Figure 2** that this is not rational at all, unless heat pump industry reaches an average COP of about 8. Such irrational moves are due to the limitations of the First-Law, which deals with only the quantity of energy but not the quality of energy. The main barrier is the unfamiliarity of the law makers with the Second-Law of Thermodynamics.

In a recent report of TTMD [6], we have shown that all EU directives and guides may be simply upgraded to the second-law by only introducing the variable ψ_R. A summary is given in **Table 2**.

Table 2. A summary of conversion from First-Law to Second Law of EU Directives.

EU Term	First Law	Second Law	Operation
Coefficient of Performance	*COP*	COP_{EX}	Multiply *COP* by ψ_R.
Primary Energy Ratio	*PER* $(PEF)^{-1}$	*PEXR*	Multiply *PER* by ψ_R.
Primary Energy Factor	*PEF*	*PEFX*	Divide *PEF* by ψ_R. Apply to electrical and thermal energy separately.
Primary Energy Savings Ratio: Cogeneration	*PES*	PES_{EX}	Scale *PES* equation with $(1.8/(2-\psi_R))$
Tonne of oil equivalent	*Mtoe*	*Mtoex*	Multiply Mtoe by ψ_R.

$$\overline{\psi}_R = \frac{\sum_{i=1}^{u}\sum_{j=1}^{v} \psi_{Ri-j} E_{xi-j} / \eta_{i-j}}{\sum_{i=1}^{u}\sum_{j=1}^{v} E_{xi-j} / \eta_{i-j}} \qquad (12)$$

Here, $\eta_{i\text{-}j}$ is the First-Law efficiency between the system nodes *i* and *j*. For example, about the heat output from the CHP unit (*i*) to a demand point (*j*) the local ψ_R value for each *i-j* connection is calculated from Equations 2 or 3. For all networks of exergy flow in the $u \times v$ nodal matrix gives the overall ψ_R value (Equation 12).

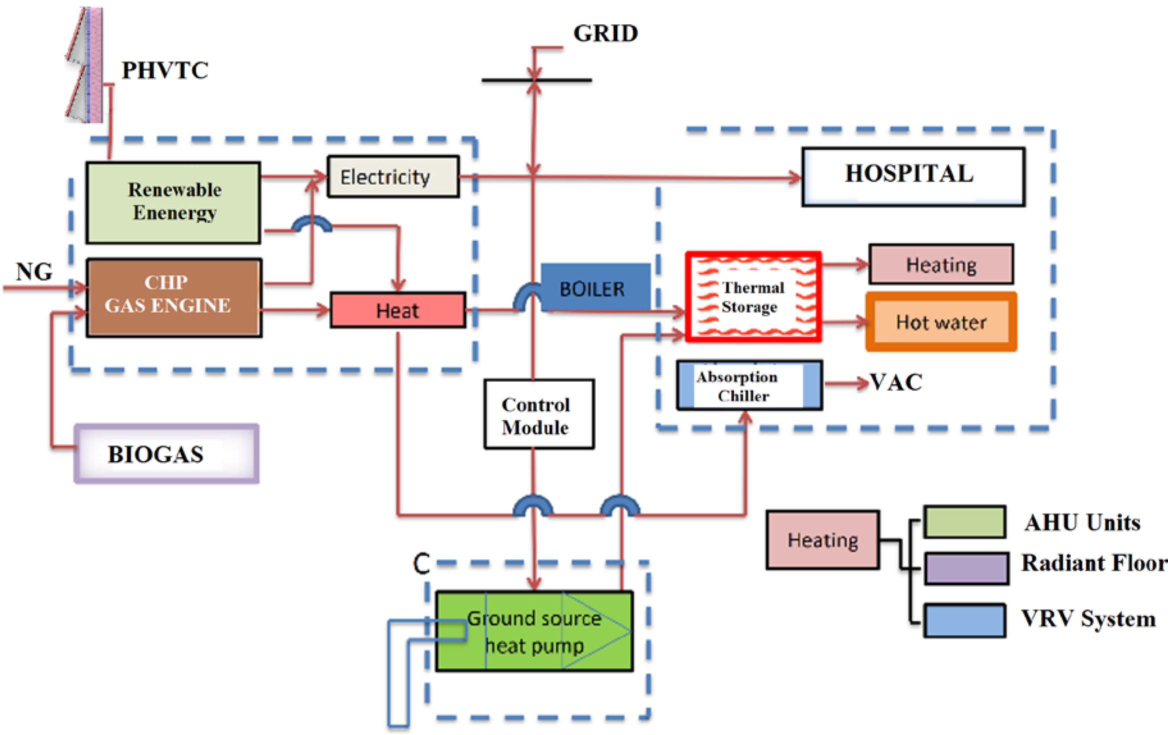

Figure 8. Electro-Mechanical System of nZEXHB.

Part of the nZEXHB requirement is that ψ_R should be at least 0.7 for a green terminal status.

Once the overall ψ_R value is determined, the compound CO_2 emissions may be calculated from

$$\sum CO_2 = \left[\frac{c_l}{\eta_l} + \frac{c_m}{\eta_m \eta_T}(1-\psi_R)\right]Q_H + \frac{c_m}{\eta_m \eta_T}E \qquad (13)$$

Here, c_l is the CO_2 content of the fuel mix of the CHP unit, η_l is its thermal efficiency. c_m is the average CO_2 content of the thermal power plants feeding the grid. η_m and η_T are the power generation and transmission efficiencies, respectively.

Discussion

From the exergy point of view, one needs a common base by converting exergy to cost or vice versa too. In this respect, the cost of exergy destruction per unit supply exergy may be embedded into cost equations, like life cycle cost analysis optimizations [6].

$$\Delta C_{EX} = c\frac{\sum \varepsilon_{des}}{\varepsilon_s} \qquad (14)$$

Here, c is the cost of average unit exergy in Euros. Average unit exergy is calculated according to EU-mix of thermal and power loads. For power, unit exergy is 1 W/W and for thermal loads at an average temperature of 333 K is 0.15 W/W.

This paper shows the need to transform to the Second-Law of Thermodynamics, if EU wishes sincerely to pursue decarbonization further with all fairness to all stake-holders. 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 mind-set and perspective towards the exploitation, generation, transformation, and utilization of our limited energy resources for a truly sustainable future that we all envision. The second-Law transformation does not need rocket-science, like many thinks. It is a simple change of the mind-set:

We should use:

- The right quality of energy, at the right application;
- At the right order, at the right time and location. ■

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