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How can green building certification systems cope with the era of climate emergency and pandemics?

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ABSTRACT

According to the second law of thermodynamics, all human activities cause exergy destructions, adding to additional root causes for carbon dioxide emissions responsibility. It means that current carbon dioxide concentrations are accurately observed, but the root causes and their potential solutions against global warming fall short of achieving the goals of the Paris agreement by almost 45% in terms of decarbonization efforts, as shown in this paper. This result applies to all activities, including the green facility concept. In this respect, the primary aim of this paper is to raise awareness about the essence of the Second Law of Thermodynamics in expanding the green facility concept to reach more effective and sustainable rating methodologies concerning the climate crisis. A new evaluating and rating model with a set of exergy-based green building metrics that relate additional carbon dioxide emissions to irreversible exergy destructions has been developed. Examples about apparently green buildings according to the First Law of Thermodynamics are given by showing that these buildings are not green due to additional carbon dioxide emissions responsibility due to exergy destructions. An airport terminal building case is elaborated. It has been shown that although part of the electricity comes from a third-party wind energy provider, it ends up with carbon dioxide emissions responsibility because it is not entirely used in exergy-rational demand points and compares less favorably with an on-site cogeneration system using natural gas by about 30% more emissions responsibility. The results and derivations of new metrics are discussed, which shed light on adding new criteria to existing green building certification programs.
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1. Introduction

1.1. Background of the present study

Kilkis, S. first introduced the concept of rational utilization of exergy by balancing the unit exergy of the supply and demand to minimize the exergy destructions [1]. Later Kilkis, B. has noted that exergy destructions may be directly translated to additional root causes of CO_2 emissions, although the observed CO_2 concentration is the same. In other words, this translation opens a wider horizon for more potential solutions against global warming. Regarding the technical committee TC 7.4 in ASHRAE titled exergy analysis for green buildings, Kilkis, B. widened his studies by noting that current green building certification programs are insufficient to approach the Paris agreement goals sustainably. Coupled with the theory and field expertise of Erten, D., the Authors developed the current study as presented herein.

1.2. Buildings and the environment

The built environment and open fields like buildings of different typologies, industrial and commercial plants, farms, and dairies are connected via district energy systems for 100% renewable heating and cooling cities, or small-scale, decentralized energy systems net-zero communities, slow cities, and net-zero buildings. They all share, prosume, and interconnect low-enthalpy, renewable, and waste energy sources with low-exergy buildings. Therefore, buildings and all other built establishments are becoming an integral part of the exterior energy, power, water, and transportation resources and networks at large and widely communicate thermodynamically with each other. Rapid urbanization and inefficient land use also carry the heat island effect, which applies to solar energy systems too. Urban areas are already about 2.5 K warmer

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Nomenclature

a, b	Linearized coefficients for the heat pump *COP*. a is dimensionless, b is in K^{-1}
A	Base area of ATES Tank, m^2
A_F	Deforested area, m^2
ALT	Residence time of greenhouse gas in the atmosphere, years
A_p	Solar insolation area of the panel, m^2
A_T	Total footage area of the building, m^2
C'	Nearly-avoidable CO_2 emission factor, See Figs. 4 and 5, kg CO_2/kW-h/(kW/kW)
C_i	Unit of radioactivity, Curie
c_K	CO_2 content of the fuel, kg CO_2/kW-h
CO_2	Carbon dioxide emissions, kg CO_2/kW-h
ΔCO_2	Nearly-avoidable CO_2 emissions (due to exergy destructions), kg CO_2/kW-h
ΠCO_2	Total emissions responsibility, kg CO_2/kW-h
COP	Coefficient of performance (of a heat pump)
COP_{EXn}	Exergy-based coefficient of performance
CP	Cases per population
C_p	Specific heat, kJ/kg
D	Diameter, m
DF	Number of mature trees cut
DU	Dobson Unit, 2.69 × 1016ozone molecules/cm^2
ELC	Exergy-Levelized Cost, €/kW_{EXpeak}/m^2
$ELCco2$	Exergy-levelized CO_2 cost, kg CO_2/kWEXpeak/m^2
EM	Embodied cost, €/kg
Ex	Exergy, kW or kW-h
GC	Geothermal system cost, euros
GWP	Global warming potential
h	Height of ATES tank, m
HFF	Heat pump factor, kW/kW
HO	Composite indoor air quality metric
$IUVB$	UVB intensity, μW/cm^2
In	Solar insolation normal to a solar panel surface, kW/m^2
k, k'	Avoidable CO^2 emissions multiplier for demand exergy, kg CO_2/kW-h (Figs. 4 and 5)
kE	Embodiment factor
L	One-way district piping length, m
$Lmax$	Exergy-based one-way maximum district piping length, mm
LR	Leakage rate, kg/h (Eq. (41))
LF	Exergy-leveling factor
Li	District circuit length of one parallel circuit, m
MRT	Mean radiant temperature, oC
N	Minimum number of young trees to be planted after deforestation
n	Number of heat pumps in tandem or the average number of floors in district buildings (Eq. (15))
nn	Number of identical parallel circuits in the district
ODI	Ozone-depleting index
ODP	Ozone depleting potential
OR	Deforestation index
P	Power, kW
PC	Panel cost,
PE	District piping network pumping capacity, kW
PEF	Primary energy factor (2.5 in EU)
PMV	Predicted mean vote
$PMVEX$	Predicted mean vote
PR	Ratio of radiant to total heating (cooling) capacity
PUE	Power usage effectiveness
Q	Heating capacity, kW-h
R, REX	Exergy-based penetration ratio of renewable energy systems by installed capacity
RUE	Resource utilization effectiveness
$RUEEX$	Resource exergy utilization effectiveness
s	Average annual CO_2 sequestration potential of a tree [kg CO_2/a],
T	Temperature, K
TC	Turbine cost, Euros
V	Wind speed, m/s
V	Base area, m^2, Eq. (54)
w	Constant in Eqs. (13) and (14)
X	Side length of ATES tank, m
Wp	Panel weight, kg
$Y(n)$	Pay-back period (Function of number of floors), Eq. (19).
y	Constant in Eq. (15)
Z	Coefficient relating boiler efficiency to the intake temperature

Greek symbols

ε	Unit exergy, kW/kW
ψ_R	Rational Exergy Management Efficiency
ηI or η	1st Law efficiency
ηII	2nd Law efficiency
Δ,d	Difference, differential
ρ	Density, kg/m^3

Subscripts

a	Air
B	Boiler
D	District
DS	District supply
dem	Demand
$design$	Design conditions
E	Electric, exit
eq	Heating or cooling equipment
f	Carnot cycle-based equivalent (virtual) energy source temperature or adiabatic flame temperature of fossil fuel, or source temperature of renewable thermal energy source
g	geothermal, ground
FAN	Fan
G	Generator
GS	Geothermal steam
H	Heat
K	Ambient thermal source or sink (like air of ground)
max	Maximum
min	Minimum
out	Outlet (temperature)
p, $pump$	Pump
pm	pump and motor combination
m	Motor
$pump$	Pump, pumping
ref	Reference
ret	Return
$solar$	Solar
sup	Supply
$test$	Test conditions
$total$	Total

Superscripts

‘	Any value after additional building insulation (Fig. 3)

Acronyms

ABS	Absorption (cooling)
ADS	Adsorption (cooling)
ATES	Aquifer thermal energy storage
BREEAM	Building Research Establishment Environmental Assessment Method

CHP	Combined heat and power (cogeneration)	nZCB	nearly-zero carbon building
DE	District energy	nZEXAP	nearly-zero exergy airport
5DE	Fifth-generation district energy	nZEXHB	nearly-zero exergy hospital building
DH	District Heating	ORC	Organic Rankine cycle (turbine)
DHW	Domestic hot water	PM	Part per million
FPC	Flat-plate collector	PV	Photovoltaic
EU	European Union	PVT	Photo-voltaic-thermal
FAA	Federal Aviation Administration	REMM	Rational Exergy Management Model
GHG	Greenhouse gas	REXC	Renewable exergy city
GSHP	Ground-source heat pump	RHC	Renewable heating and cooling
HVAC	Heating Ventilating and Air-Conditioning	TSE	Turkish Standards Institute
IAQ	Indoor air quality	ULT	Ultra-low temperature
IEA	International Energy Agency	UN	United Nations
IGA	Istanbul Grand Airport	US DOE	United States Department of Energy
LEED	Leadership in Energy and Environmental Design	VLT	Very-low temperature
LowEx	Low exergy	ZEB	Zero-energy building
NZEB	Net-zero Energy Building		
NZEXB	Net-zero Exergy Building		
nZC	nearly-zero carbon		

than rural areas [2]. While 100 renewable heating and cooling with solar energy is envisioned, solar photovoltaic systems also capture solar heat and amplify this temperature difference. The temperature difference has carbon dioxide emissions responsibility due to the increase of the cooling loads. Therefore, a careful balance of renewable energy systems and the global crisis must be sought and maintained. Current green building programs do not acknowledge this side effect of solar energy systems, which primarily depend on how the green buildings are designed, built, and operated. Within such a complicated nexus and climate emergency, the EU countries have developed two road maps, namely, 100% renewable energy utilization and total electrification with renewable energy sources using heat pumps for building heating and cooling [3]. For example, a claim based on the 1st Law that heat pumps running on renewable electricity are not responsible for CO_2 emissions is false. Electricity, whether generated from renewable energy sources or fossil fuels, has an exergy of 0.95 kW/W, which means that 95% of the electrical energy may be utilized in useful works in a wide range of applications. The so-called exergy is the useful work potential of a given amount or flow of energy, ideally defined by the Carnot Cycle [3,4]:

$$Exergy\ (Quality) = \left(1 - \frac{T_{ref}}{T_{\sup}}\right) \times Energy\ (Quantity) \tag{1}$$

If T_{ref} is chosen to be 283 K (Winter ground temperature) and a ground-source heat pump system provides heat at 320 K to the district, the useful work potential will be only 0.115 kW/kW of the quantity of heat supplied. The heat pump uses electrical power, and according to the 2nd law, the coefficient of performance, *COP* must be high enough that the exergy of electricity and the thermal exergy of the heat supplied must be even at least:

$$COP \geqslant 0.95/0.115 = 8.3\ \left\{2^{nd}\ \text{Law}\right\}$$

If *COP* is <8.3, part of the electrical power exergy will be irreversibly destroyed. For example, if the heat pump provides heat at 320 K at a reference temperature of 283 K to satisfy demand, and after noting that electricity consumed by the heat pump has a unit supply exergy of 0.95 kW/kW supply and demand exergy becomes even at about 8.3:

0.95 kW/kW/(1–283 K/320 K) = 8.21. Because this calculation is based on the ideal Carnot cycle, the limit has been rounded to 8.3. If the *COP* is less than this limit for this specific case, exergy mismatch occurs and must be offset by someone, sometimes by using some type of fuels, causing additional CO_2 emissions responsibility. This emission is called nearly-avoidable emissions, ΔCO_2. Therefore a 'green building' and 'zero-carbon building by today's definitions may not have direct emissions but still be responsible for additional emissions because it destroys exergy even if it employs a heat pump operated with renewables or uses on-board solar energy systems. The required *COP* mentioned in this example is quite above regarding current heat pumps in practical applications unless they are in a cascade [5]. These arguments show that the 2nd Law is essential to redefine green buildings because a green building, according to the 1st Law, may not be necessarily green and carbon-free.

Despite these concerns, an important asset for decarbonization is the widely but sparsely available low-exergy renewable energy sources and waste heat, which were ignored primarily because the building heating and cooling systems are not compatible yet with low supply temperatures in heating and high supply temperatures in cooling. Secondly, as mentioned above, their low exergy may be problematic when temperature adjustments are necessary with heat pumps or other conventional energy conversion systems like boilers in temperature peaking. Thirdly, these energy sources are sparsely distributed and interrupted in nature. Therefore, it becomes necessary to collect these energy sources from several points, store them as required, and then distribute heat and cold to the buildings. All of these functions call for district energy systems. Therefore, low-exergy district heating and cooling systems are attracting more attention than before.

1.3. Wide availability of Low-Temperature heat sources

Fig. 1 shows that waste heat sources from different sectors below 100 °C are abundant worldwide, 63% of all the available waste heat sources [6]. Out of the 63% of low-temperature heat sources, about 50% of them are below 50 °C. Fig. 2 shows the case for geothermal energy. Carnot exergy, ε of any waste heat below 100 °C may be quite low (ε < 0.24 kW/kW at 100 °C, and a reference temperature of 283 K. Although this is not a critical problem as anticipated, these resources were often ignored. Instead, today's critical problem is the significant mismatch between the low Carnot exergy of the widely available low-temperature sources and the existing indoor comfort heating equipment.

Low-temperature heating will be feasible by a closer exergy match. Therefore, all green certifications must be redefined by

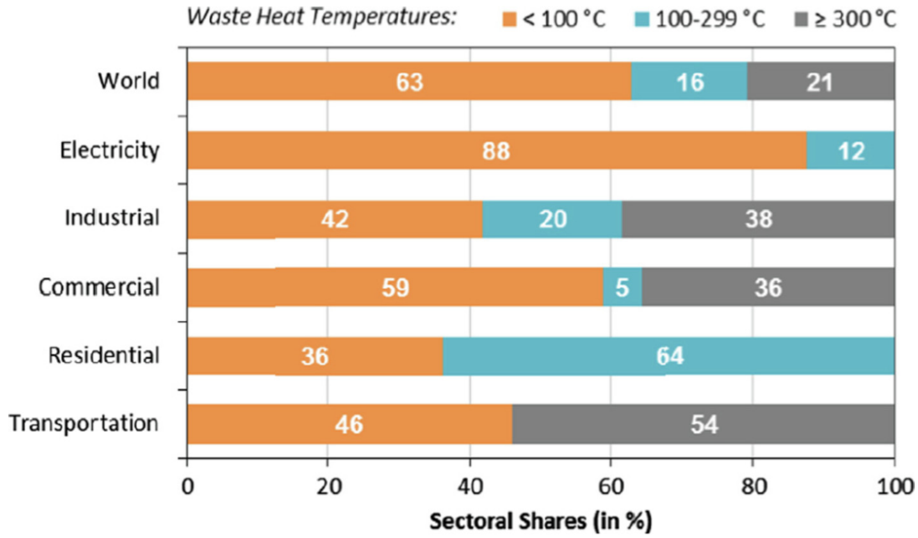

Fig. 1. Worldwide Sectoral Shares of Waste Heat Temperatures [6].

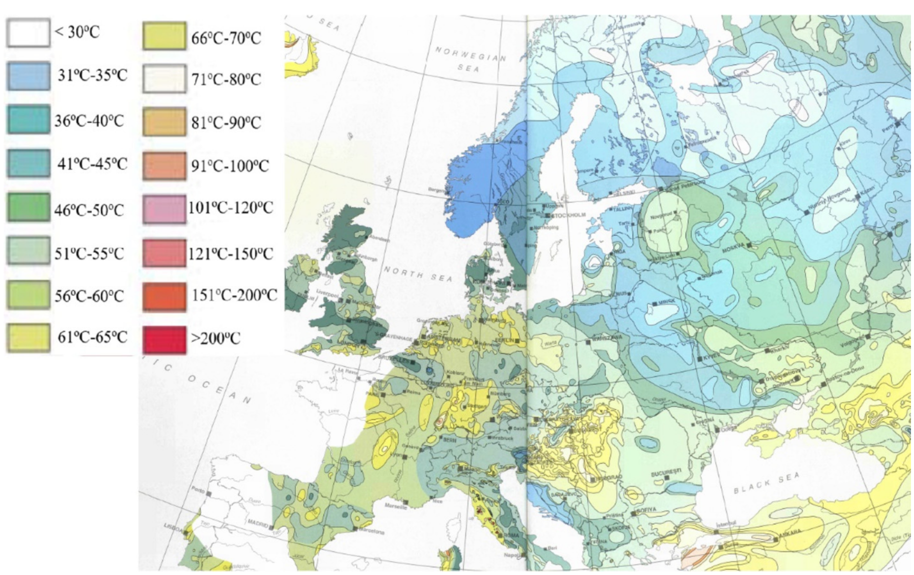

Fig. 2. Shallow Geothermal Resource Temperature Atlas for Europe [13,14].

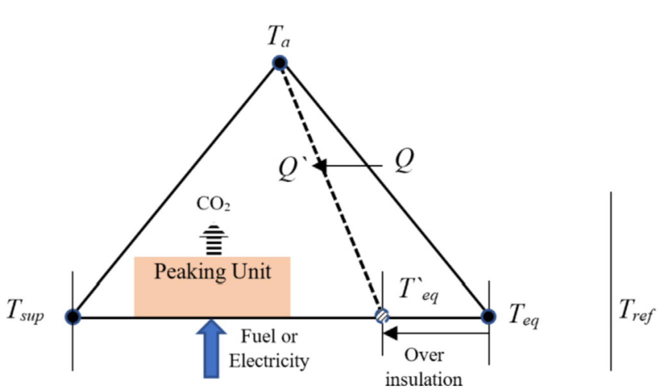

Fig. 3. Conflict Between Low-Temperature District Heating and Buildings (Drawn by Authors) [17].

the exergy concept for decarbonization towards the Paris agreement [7,8].

1.4. The conflict between the existing building stock and low-temperature heating

In many EU countries, half of the residential stock was built before 1970, when the first thermal efficiency regulations were not available yet [9]. Most of these buildings are energy-inefficient, and their heating equipment was designed for high supply temperatures. Therefore, there is a significant conflict between the many old buildings that demand high supply temperatures and the new EU roadmap towards ultra-low temperature district energy systems, namely the Fifth-Generation District Energy (5DE) systems with temperatures as low as 35 °C (T_{sup}) [10,11]. In the Framework of IEA Annex 37, a comprehensive compilation of research was carried out on low-temperature heating and its potential implications and the so-called side effects [12]. They considered floor heating, wall heating, oversized radiators and convectors, and air heating. The potential impacts of low-temperature heating from the perspective of buildings about indoor air quality (IAQ), comfort, and energy have been further investigated by Eijdems, Boerstra, and Veld, without considering the conflict between energy supply temperature and the equipment demand temperature [11]. For public understanding and acceptance, they termed the low-exergy (Temperature) energy as 'low valued' energy. They overviewed the impact of low-temperature supply to heating equipment for several types of equipment, including radiant floor and wall panels, low-temperature air heating. They qualitatively claimed that IAQ and sensation of comfort improve mainly by using radiant panels, which already permit low temperatures for operation. However, they did not study how low-temperature heating may be made possible by designing new equipment and oversizing the existing equipment, only noting that heat pump *COP* values may increase due to reduced temperature deficit between the supply and demand. Fig. 3 models this conflict of at least 35 °C of temperature deficit. When a low-temperature source is provided at T_{sup}, this figure also shows that over insulation of the old buildings may reduce the gap because the heating supply temperature for the terminal equipment is reduced while the thermal load of the building decreases. If fossil fuels are used for heating, CO_2 emissions are directly reduced. If renewables are used, then the ΔCO_2 emissions responsibility decreases with a shift of T_{eq} on the exergy flow bar.

However, additional thermal exergy must still be provided by temperature-peaking units at the expense of additional fuel, which defeats the purpose of decarbonization. Over insulation of the buildings may be a weak option because of embodiments and thermo-physical constraints. Even if this is possible, then the building heat loads may be somehow decreased, which will reduce the supply temperature requirement of the terminal equipment, T_{eq} to T'_{eq}. In the same token, any temperature peaking unit may increase the design supply temperature to T'_{eq}. It is possible to determine an optimum relation between the over-insulation process and equipment oversizing regarding the Rational Exergy Management Efficiency (REMM), ψ_R, given in Eq. (2) [15]. T'_{eq} is the supply temperature required by the heating equipment after optimally oversizing it for minimizing the need for temperature peaking. T_a is the indoor design temperature. In cooling applications, where $T_a < T_{ref}$, the same equation may be used, provided that parentheses are replaced by absolute value bars [16].

1.5. Nearly or net-zero buildings definitions

ZEB is not necessarily a response to the success of the so-called fifth-generation district energy systems (5DE), which utilize low-temperature heat. On the other hand, a zero-energy building is not necessarily a low-temperature, low-exergy building. For example, consider a ZEB installation, which generates power with solar PV panels and uses this power directly in high-temperature processes. Therefore, although this plant is a zero-energy building, it does not fit into the 5DE strategy because it demands high-temperature heat and generates this heat with high-exergy electricity. In this respect, ZEB or NZEB definitions are necessary but not sufficient conditions.

$$\psi_R = \frac{\varepsilon_{dem}}{\varepsilon_{\sup}} = \frac{\left(1 - \frac{T_{ref}}{T_a}\right)}{\left(1 - \frac{T_{ref}}{T_{\sup}}\right) + \left(1 - \frac{T_{\sup}}{T'_{eq}}\right)} \tag{2}$$

On the other hand, these buildings must become compatible with low-supply temperatures (in heating) or high supply temperatures (in cooling) by retrofitting them with new heating or cooling equipment [18]. The incompatibility of existing heating equipment in the existing building stock, 50 years old or older, is a fundamental barrier for 5DE systems. The key to the solution is a composition of suitable retrofits with minimum additional embodiment and operating CO_2 emissions responsibility. High global energy consumption in the buildings requires developing low-temperature heating systems and implementing them in new and retrofit buildings. Sarbu and Sebarchievici [19] proposed floor heating systems compared to conventional radiator systems with ground-source heat pumps (GSHP) rather than proposing innovative products. Their study did not acknowledge that installing radiant floor systems in existing buildings is quite difficult.

Furthermore, in the absence of the 2nd Law in their analysis, they did not recognize that heat pumps operating with electric power are also responsible for nearly-avoidable emissions and ozone depletion due to their refrigerant leakages. Hesaraki et al. [20] proposed ventilated radiators. In this system, attached fans enhance the convection heat transfer and increase the heating capacity at lower supply temperatures. However, their study excludes the electric power consumption of fans. The high exergy demand of the fans (0.95 kW/kW) is not balanced by the exergy of additional thermal capacity (in the order of 0.15 kW/kW) even with the decrease of the electrical power demand of the heat pumps due to their increased *COP* at lower supply temperatures required by ventilated fans. None of the low-temperature heating research addresses such exergy-based issues, and their low-temperature heating system proposals are limited to radiant panels with or without heat pumps.

After reaching a standard definition of Zero-Energy Buildings by the US DOE in 2015, in collaboration with NIBS, a widespread lack of scientific clarity and comprehension still exists in the green building business. With the emergence of 100% Renewable Heating and Cooling in the EU (100%RHC), it becomes clearer that if the main objective is decarbonization against global warming, then the 1st Law (Energy) is not sufficient to define, design, rate, and metricate 'zero' buildings and a new definition in terms of the 2nd Law (Exergy) are necessary.

1.6. Challenges of current methods

Figs. 4 and 5, which graphically demonstrate the lack of understanding of the root causes of global warming, also explain everything about missions, novelty, urgency, and integrity of this study.

The solar PV system generates power first and destroys exergy downstream by losing the opportunity of generating thermal power like in a solar photovoltaic-heat panel (PVT). None of the current green facility models and certification programs recognize exergy destructions and related emissions responsibility. Another example is an electrically-driven heat pump with a given COP, which is used for heating. In this case, the order of exergy destruction (upstream of demand) and useful application changes, but the material and the method presented herein remain the same, except the multiplier c, which depends on whether major exergy destruction occurs upstream or downstream. In addition, a heat pump is responsible for further emissions due to refrigerant leakage at a rate, LR; even ozone depletion potential is zero with a non-zero global warming potential (GWP). These two extreme cases indicate that the new exergy-based material and method presented in this paper is universally applicable to any process, provided that the problem is brought to a real or virtual platform of the ideal Carnot Cycle.and if the supply temperature from the heat pump decreases because *COP* value decreases, then for a given heating demand unit exergy of $\varepsilon_{dem,}$ ε_{des} (exergy mismatch) increases, and eventually, ΔCO_2 critically increases.

None of the current green building certification programs include exergy destructions and associated ΔCO_2 terms, exemplified in these figures. They largely fall short by about 80% of the rec-

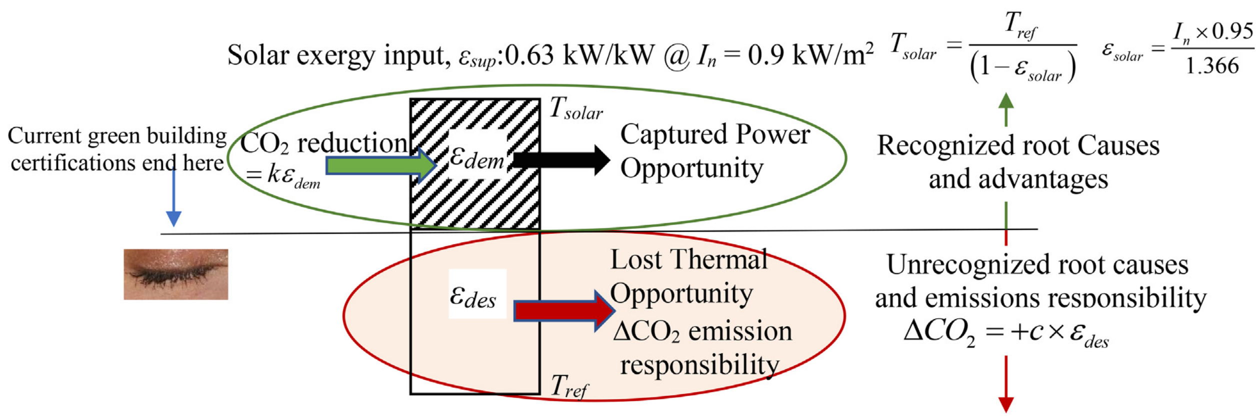

Fig. 4. Exergy Destructions of a Solar PV System (Drawn by Authors).

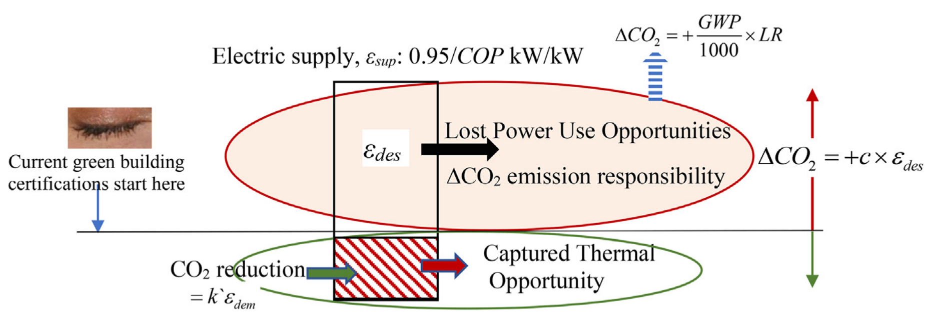

Fig. 5. Exergy Destructions and Emissions Responsibility due to Refrigerant Leakages (Drawn by Authors) On the other hand, because of the following simple relationship; $\varepsilon_{des} = \varepsilon_{sup} - \varepsilon_{dem}$,

ognized emission causes in addressing the global warming problem for guiding strategists to more accurate and complete green building designs and rating systems. This study aims to cover all the gaps mentioned and provide a new holistic model by correcting human vision to resolve the current short-sighted measures and rating systems for achieving the right quest of battling global warming. This aim is achieved by recognizing the currently unrecognized or unrevealed root causes of carbonization as a function of the degree of rational utilization of energy resources, represented by the primary metric of this study, namely, ψ_R. The globally current average value of rationality is 0.20. Therefore, strategists do not recognize an additional 80% of the root causes emanating from exergy destructions. This deficiency leads to a serious deficiency in achieving the goal of the Paris Agreement. In other words, potential solutions fall short by about 45% (0.8/1.8).

$$\sum CO_2 = \underbrace{CO_2}_{\boxed{\text{Recognized}}} + \underbrace{CO_2 \times (1-\psi_R)}_{\boxed{\text{80\% Unrecognized}}}$$

2. Plan of the study: advanced concept of green facilities

2.1. New Frontiers of green building concept

Frontiers of green are expanding from building to cities and even beyond. A 100% renewable city in terms of the 1st Law means that all energy demand is supplied by renewable energy sources, including waste heat. This definition falls short of answering how renewable energy sources are used in the city. Exergy mismatches are more critical in low-temperature heating and high-temperature cooling, as explained in Figs. 4 and 5. The key potential assets of the fifth-generation (5DE) district systems are very low supply temperatures, and second, complete electrification with heat pumps for temperature peaking and cooling. Both measures are directly subject to the 2nd Law, which is not accounted for yet.

According to the Heat Roadmap Europe Data, if the urbanization trend continues, almost half of Europe's heat demand could be met by district heating (DH) by 2050 [21]. At least eight European countries have already achieved high shares of renewables in their existing DH systems. However, the window of opportunity may be expanded only with very-low temperature systems (VLT) to utilize low-exergy renewable and waste energy sources. One handicap is the return temperatures, which may not be too low, like 25 °C (Table 1).

Today's architects need to factor in an additional but important dimension, namely the relationship between the ceiling height and virus spread like COVID-19, particularly in large buildings like airport terminals [11]. Another issue is the necessity of accurately metering the exergy exchange of the consumer/prosumer with the district [22]. Furthermore, the difference between the supply and return temperatures needs to be over 2 °C because of accurate, and more precise control requirements and proportionately increased pumping power requirements of the heat exchangers involved. Finally, legionella risk must be taken into account, and

Table 1
Different Heating System Designs According to Operational Temperatures [21].

System	Supply Flow	Return Flow
High temperatures (HT)	90 °C	70 °C
Medium temperatures (MT)	55 °C	35–40 °C
Low temperatures (LT)	45 °C	25–35 °C
Very low temperatures (VLT)	35 °C	25 °C

domestic temperature peaking systems may be necessary, usually in the form of on-demand electric heaters. There are successful VLT or ULT (Ultra-Low Temperature) DH applications leading to green cities or the so-called 100% Renewable Heating and Cooling cities (100%RHC). One of such applications is located in Bjerringbro, Denmark, which combines heating and cooling services in tandem. Groundwater between 6 °C and 12 °C satisfies the cooling load of an industrial plant. The waste heat of cooling is peaked at 47 °C by the heat pump station for about 20 single-family homes [23]. CHP units and boilers also supplement the system. Yang and Svendsen [23] acknowledge the importance of exergy match in their paper but do not further express the associated nearly-avoidable CO_2 emissions responsibilities of their system. However, a direct relationship has to be taken into account between the nearly-avoidable CO_2 emissions and exergy destructions emanating from the exergy mismatches. Li and Svendsen [24] carried out energy and exergy analyses for a conceptual low-temperature district heating system. Their main conclusions were reduced heat losses in the district piping leading to less exergy destruction in the pipe network and better exergy match with lower supply temperatures. Voloshchuk, Gullo, Sereda [26] formulated the avoidable exergy destructions in residential heat pumps but did not establish a quantified link to CO_2 emissions responsibility [25]. Kilkis and Kilkis tackled the emissions responsibility issue earlier in their paper, linked with the average number of floors in a district energy system [26,27].

Regarding renewable energy sources, Meisam and Arabkooshar [27] carried out exergy, economic, and environmental analysis for parabolic trough collectors for district cooling with absorption chiller of Aarhus University and presented the exergy destructions at every major step of the process. They claimed a pay-back period of 7.5 years and predicted a sparing of 180,000 tons of CO_2 emissions over 20 years. However, this prediction involved only direct CO_2 emissions savings and did not consider nearly-avoidable CO_2 emissions according to their already calculated exergy destructions. The closed-circuit distance between the district plant and the district is important and must be optimized against a maximum distance according to exergy considerations and subsequent CO_2 emissions minimization [28]. It is also imperative that air-to-air heat recovery systems need to be revisited in terms of their 'green' performances in terms of exergy [29]. On a smaller scale of district heating and cooling, Nami and Moghaddam [31] have analyzed the exergy, economy, and environmental attributes of a geothermal microsystem for domestic applications [30]. They considered an absorption chiller, an ORC, and ancillaries with real geothermal resource data for the Izmir region in Turkey. They did not relate their calculations to CO_2 emissions and did not consider the high CO_2 content of the geothermal source in the west Aegean graben either. Keçebaş et al. applied a specific exergy cost method to a geothermal district heating project west of the same graben, Afyon [32]. At the wellhead, geothermal fluid was settled first in an open pool for cooling to a temperature compatible with the thermoplastic piping and then distributed the heat without paying attention to the exergy of the electricity demand of pumping and the geothermal exergy supplied. An ORC system to utilize the exergy in power generation was recently added. None of those authors have addressed the nearly-avoidable CO_2 emissions. Unless all these technical solutions are optimized on an exergy basis, the use of low-temperature resources will be almost useless, except for Denmark, where heating equipment was already overdesigned such that 80% of buildings may accommodate low-temperature systems [33]. A major problem that will arise soon is due to global warming, which increases cooling loads, and these loads will exceed heating loads such that by 2050, air conditioning loads will be the largest power demand, as predicted in Fig. 6 [33]. Exergy destructions in existing cooling equipment are larger compared to heating due to lower unit demand exergy. Therefore ΔCO_2 term will be larger towards the Paris Agreement. Increasing cooling loads present another challenge.

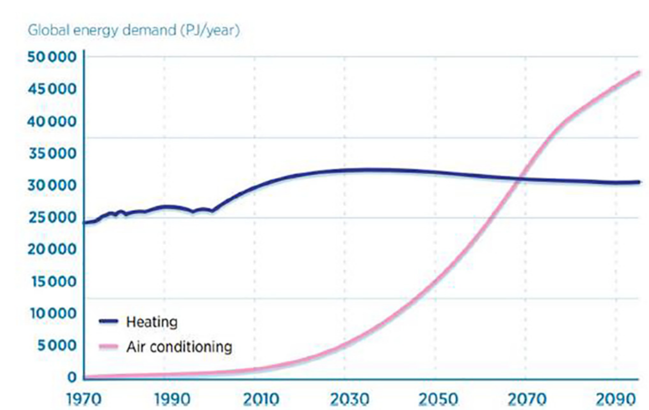

Fig. 6. The Global Trend for Heating and Air Conditioning Demand in Buildings [33].

2.2. Quadrilemma in 5DE

Fig. 7 shows today's quadrilemma of green buildings. There are six vectors, namely 1- social welfare and health, 2- energy spending, 3- exergy destructions (during energy spending), 4-nearly-avoidable CO_2 emissions, namely ΔCO_2 due to exergy destructions, 5-CO_2 and particulate emissions ($PM_{2.5}$) due to energy spending, and 6- global warming and ozone layer depletion: *Climate Emergency*. These vectors are boxed into four conflicting dimensions. In this study, an economic dimension was added, and the vectors of Fig. 7 were re-grouped for simplicity for green buildings and dis-

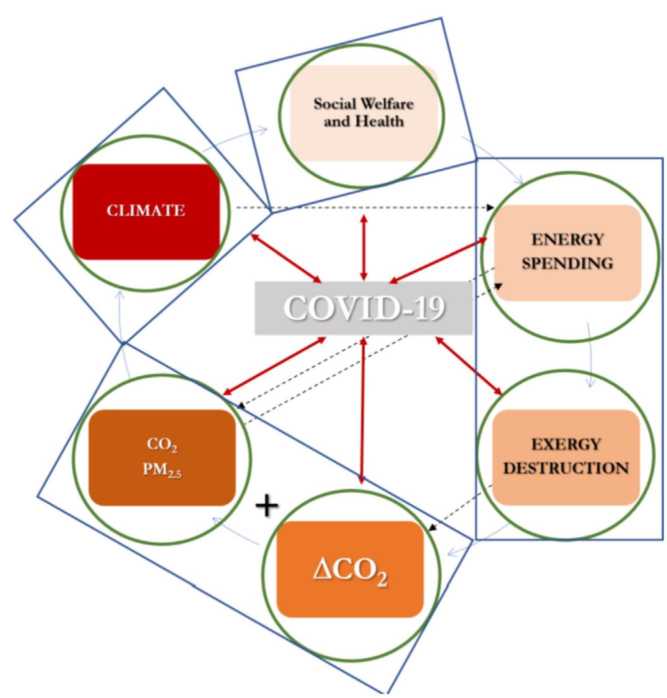

Fig. 7. Quadrilemma of Green Concept Against Climate Emergency (Drawn by Authors) [22]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

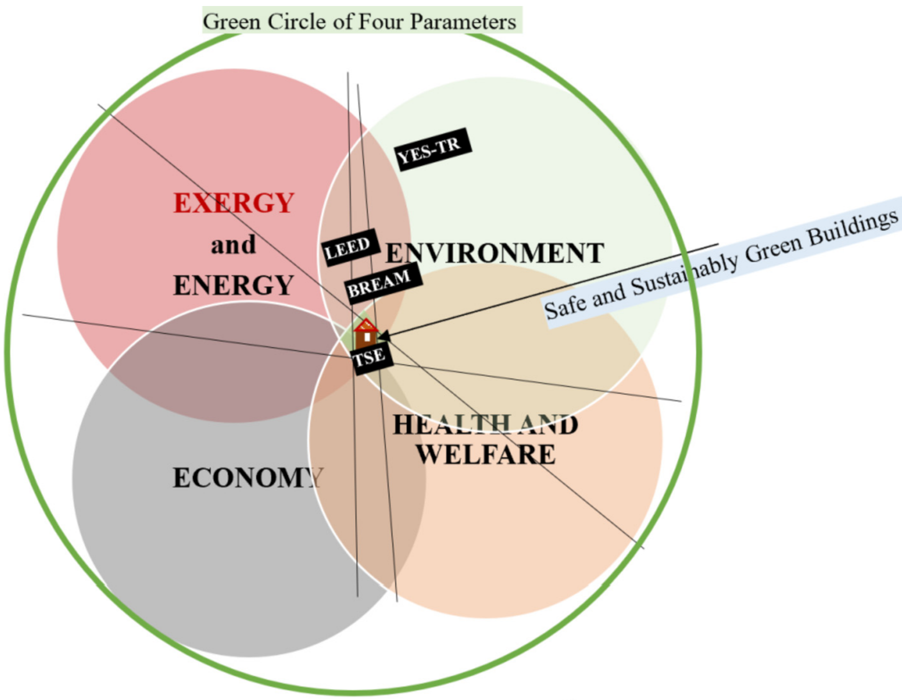

Fig. 8. Simplified Four Conflicting Parameters of the Built Environment and the Exergy-Based Green Buildings (Drawn by Authors). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

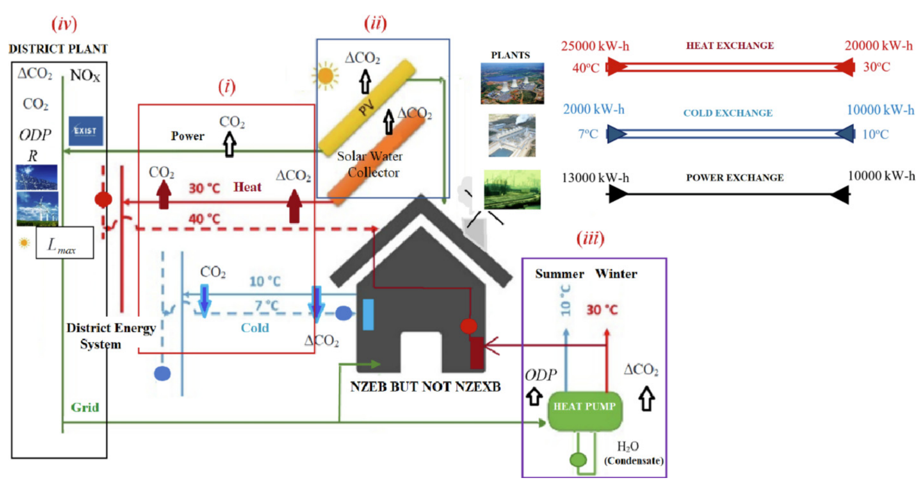

Fig. 9. A 'Green' and Net-Zero Prosumer Building Connected to a District Energy System (Drawn by Authors). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tricts, shown in Fig. 8. None of the existing green building certification programs recognize the quality of energy (Exergy) involved.

Fig. 8 shows that these programs stay out of the small best compromise area, where the four major conflicting parameters overlap. Also, several limits remain unaccounted for in terms of exergy. Recently the COVID-19 pandemic became a bilateral relative with all of them (see Fig. 7). Therefore, a preliminary conclusion may be drawn such that it is time to include the concept of *Pandemic Resistant Buildings* to the green metrics under a broadened title of safe buildings. Green certification programs like LEED and BREEAM are on the energy side only. They, in essence, consider energy and economy as one parameter. So, their first flaw is that they deal only with three parameters.

3. Case study

Fig. 9 exemplifies a so-called net-zero energy solar prosumer. This building is free from fossil fuels. On an annual basis, it exchanges power, heat, and cold with the district energy system, which, irrespective of their different energy qualities, sum identically to 40,000 kW-h/year. This prosumer is responsible for CO_2 emissions at four distinct areas, namely, *i*- power, heat, and cold exchange network of the district, *ii*-Solar PV and solar collector system, *iii*- The heat pump, and *iv*-district power and heat plant.

Two different CO_2 emissions responsibilities were identified. One is direct emissions due to exchange differences between heat and cold production (Energy quantity) on both sides. The second

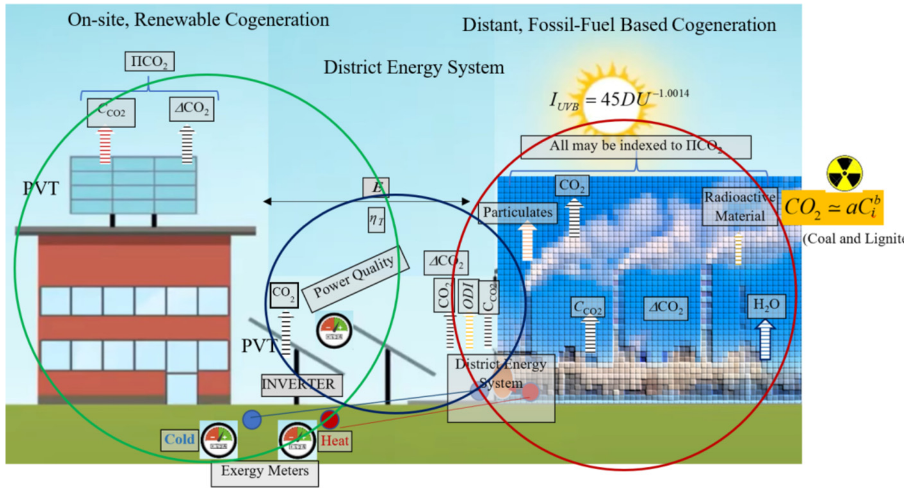

Fig. 10. Background of a Net-Zero Prosumer Building in the Built Environment (Drawn by Authors).

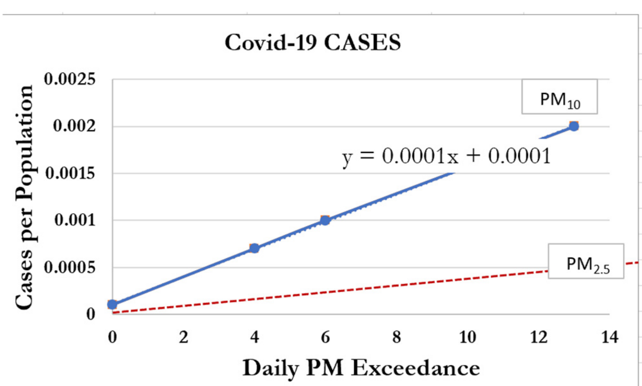

Fig. 11. NO_X Emissions Exceedance and Covid-19 Cases per Population, *CP* (Drawn by Authors).

one is due to exergy (Energy quality) imbalances between the heat and cold exchanges, namely nearly-avoidable emissions, ΔCO_2. Furthermore, due to the deficit of 5000 kW-h of heat on the building side, the central district plant will spend more fuel, most probably, fossil fuels. If this is a lignite or coal plant, water vapor released through the cooling towers (also from any kind of power plant) and radiation fallout from the stack to its close vicinity have greenhouse and safety effects on the environment. Net-zero buildings, whether they are stand-alone (except electricity) or district connected, must also be held accountable for these effects, depending upon the proportion of the grid power and heat they receive externally. It is also important to trace the in-house use of power and heat. For example, if a green building generates power with its roof-mounted PV array but uses it directly in resistance heating for indoor comfort, it must be held accountable for the avoidable emissions. Furthermore, the heat pump of this sample building is responsible for ozone depletion due to usual refrigerant leakages, which may be related to CO_2 emissions. Recently developed refrigerants have almost zero *ODI*, but current certification programs do not consider *ODI* and the type of refrigerants.

$$ODI = \frac{0.1GWP^{0.03}}{(1-ODP)}\left(\frac{ALT}{1}\right)^{0.01} \quad . \ \{ODP < 1\} \tag{3}$$

$$CO_2 = \left(\frac{L}{E_{xsup}}\right) \times GWP \tag{4}$$

Concerning the example in Fig. 9, they are becoming an important asset for EU countries and others globally to reduce ozone depletion and global warming, which are related through Eqs. (3) and (4). However, Fig. 10 shows how a building background upstream is important. There are two additional components of CO_2 emissions, namely from coal and lignite plants and the ozone depletion effect of cooling towers.

4. Method

4.1. Buildings and COVID-19

It is estimated that buildings alone with at least 35% share in global energy consumption are responsible for almost 10% of the Covid-19 cases due to their share of climate emergency and pollution. This finding excludes the indoor risks of buildings. The relationship between the built environment and the Covid-19 pandemic has been derived as given in Eqs. (5), (6), and Fig. 11:

$$\underset{\textbf{Total}}{\Pi CO_2} = \underset{\textbf{Direct}}{CO_2} + \underset{\textbf{N.Avodable}}{\Delta CO_2} + \underset{\textbf{Radiation}}{aC_i^b} + \underset{\textbf{Ozone Depletion}}{d(I_{UVB})^e} \tag{5}$$

$$PM_{2.5} = f\Pi CO_2 \tag{6}$$

The global average factor *f* 7 is about 0.05 according to energy statistics, which relate NO_X and CO_2 emissions of different sectors and machinery. As daily PM exceedance increases due to overall emissions responsibility from the built environment in Eqs. (5), (6) derived by the Authors of this paper, and Eq. (7) show that the number of cases increases proportionately. ΔCO_2 is about 80% of CO_2. Therefore about 1.8 CO_2 term is the dominant factor.

$$CP = (0.000035f \times \Pi CO_{2exceedance} + 0.0001) \tag{7}$$

This expression requires new standards to limit ΠCO_2 instead of only the direct CO_2 emissions. Therefore, any green-candidate building must also be evaluated regarding their external responsibilities for pandemics and other illnesses, with new pandemic-resistant building programs in green certification programs.

Fig. 12 shows the evolution of district energy systems starting from the past century. 5DE brings new challenges like increasing the pipe diameters to offset the district pumping power demand due to smaller temperature drops in the circuit necessary at such low temperatures. The lower the supply temperature is, the higher is the sensitivity of exergy variations. Therefore, four tiers of district energy are identified in Figs. 12 and 13, reminding that those buildings are not alone anymore and prone to a whole new concept

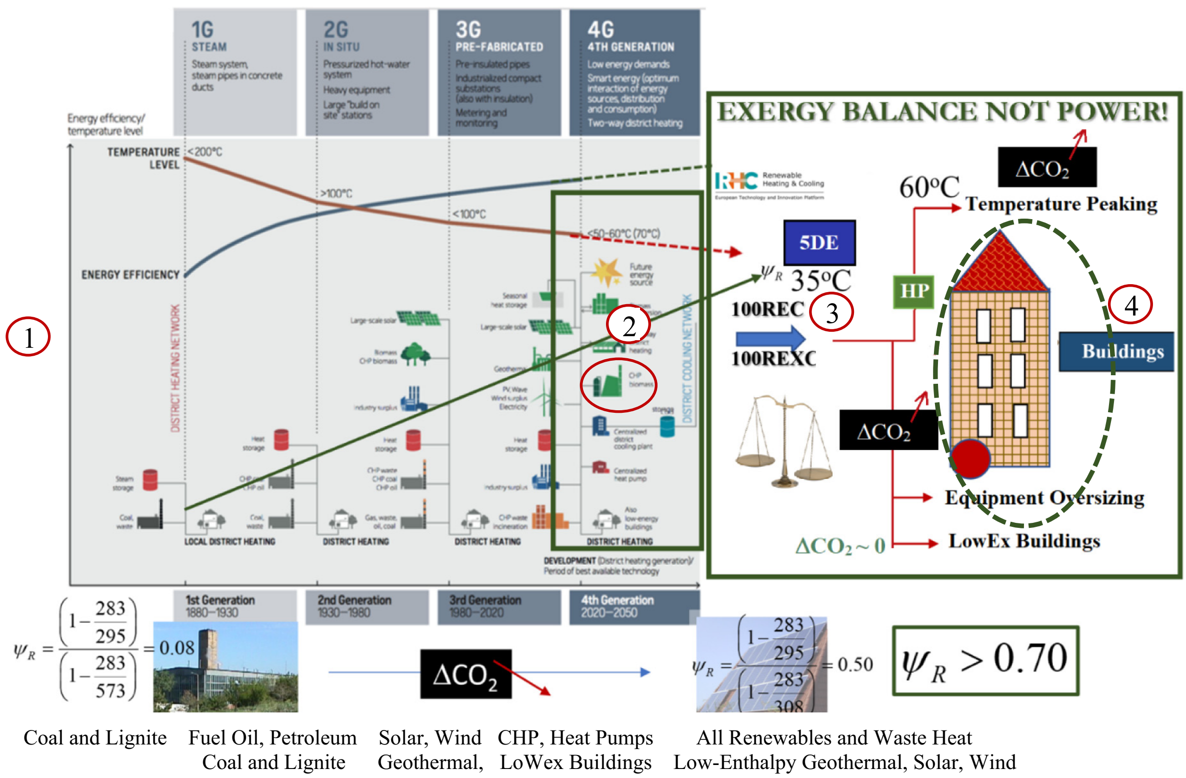

Fig. 12. Evolution of District Energy and Cogeneration (CHP). Adopted and Modified From [34].

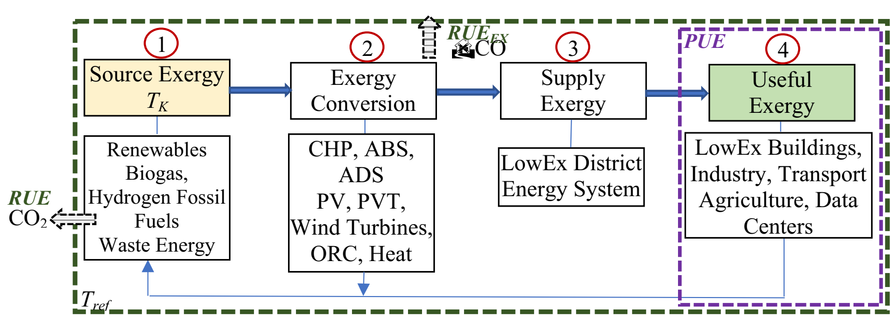

Fig. 13. Four Tiers of LowEx District with Circular Exergy (Drawn by Authors).

of holistic enclosure of a diversity of many buildings and energy sources and systems. For example, in conventional rating systems, the power utilization factor *PUE* is concerned with the quantity of electricity, like a 'green' data center. However, it does neither recognize nor question where the electricity comes from. In power generation, CO_2 emissions responsibility and fossil fuel spending may be extensive. For a better understanding of the environmental footprint of district energy systems, new metrics, namely *RUE* and $RUE_{EX,}$ were defined.

$$RUE = \frac{\text{Total Source Energy Dedicated}}{\text{Useful Energy Available}} \simeq \frac{1}{\eta_I}\ \{\text{Power and Thermal}\} \tag{8}$$

$$RUE_{EX} = \frac{\text{Total Source Exergy Dedicated}}{\text{Useful Exergy Available}} \simeq \frac{1}{\eta_{II}}\ \{\text{Power and Thermal}\} \tag{9}$$

Useful exergy is obtained after the exergy storage, and all parasitic exergy losses are deducted from the total exergy supplied to a district. RUE_{EX} is an indicator of the avoidable emissions, ΔCO_2, because of exergy destructions, ε_{des} in a thermal exergy-dominated district, Eq. (10) is the corresponding metric:

$$\Delta CO_2 = 0.27\varepsilon_{des} = 0.27\left(1 - \frac{\varepsilon_{sup}}{RUE_{EX}}\right)\ \{\text{Based on Thermal Exergy Destructions}\} \tag{10}$$

Similarly, direct emissions per kW-h energy may be expressed in terms of *RUE* if fossil fuels are used:

$$CO_2 = c_K \times RUE\ \ \{\text{Fossil Fuel Use per 1 kW} - \text{h}\} \tag{11}$$

If ideally, RUE_{EX} approaches one, ΔCO_2 approaches zero. If *RUE* approaches one, CO_2 approaches c_K.

District energy systems clustered around a CHP system in Fig. 13 give the opportunity to follow up, metricate, and control all phases from fuel to demand by considering *RUE* and RUE_{EX},

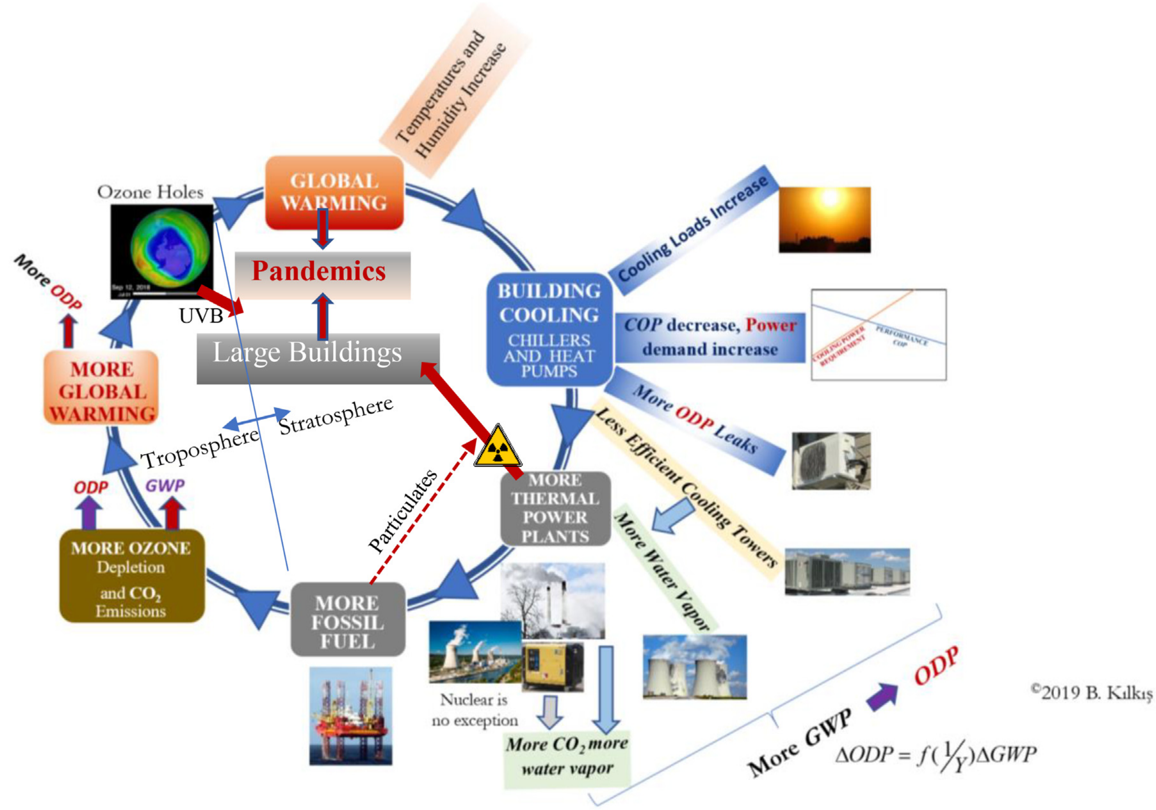

Fig. 14. The Vicious Cycle of Cooling, Pandemics, and Global Warming [35].

which also simply show the CO_2 responsibilities. Fig. 14 shows the vicious cycle of cooling, pandemics, and global warming [35].

4.2. New cooling technologies and the 2nd Law:

The power + heat to cold ratio is unsuitably decreasing with global warming. Therefore, new cogeneration systems must employ absorption and or adsorption machines to supply cold instead of electric chillers. This transition will also reduce the demand for cooling towers with the greenhouse effect [36] by utilizing their waste heat. In conclusion, it may be stated that none of the following subjects are considered in the current green building certification programs.

4.3. Conflict between Low-temperature district heating and existing buildings

In 5DE systems, energy metering and nZEB or NZEB ratings become more sensitive to moderate temperatures. Therefore, calorimeters need to be transformed into exergy meters for fair exergy-based charging to customers. Eq. (10) establishes such a customer charging platform and leads to a new definition, nZEXB. Sensitivity increases with the square of decreasing T_{sup}. Therefore, exergy calculations need more accurate and precise measurements. In cooling, the required sensitivity is relaxed at higher supply temperatures. Therefore, LoWex buildings are advantageous in cooling and heating for precise control of exergy supply and demand for maximum ψ_R.

$$d\varepsilon = \frac{g}{T_{\text{sup}}^2} dT_{\text{sup}} \quad \{g: 79 \text{ for heating}, -120.2 \text{ for cooling}\} \tag{12}$$

4.4. Absence of exergy rationale in district energy system piping and infrastructure

In green certification, the size of the district that a green building is connected must be important. The one-way district piping distance, $L_{max,}$ compares the exergy of the thermal power, namely $\dot{Q}_D$, which is delivered by the district consuming exergy for district pumping, P_E [29]. The following formulations show that L_{max} must be determined first in terms of the 2nd Law.

$$L_{\max} \leqslant \left(0.273 - \frac{79}{T_{DS}}\right) \cdot \frac{(\eta_P \eta_m)}{w} \cdot \dot{Q}_D^{1.5} \frac{32}{0.95\sqrt{5\pi\rho C_p[0.273T_{DS} - 79]}}$$
$$\{\text{In district heating and } T_{DS} > T_{ref}\} \tag{13}$$

$$L_{\max} \leqslant \left| -0.4 + \frac{120.2\ \text{K}}{T_{DS}} \right| \cdot \frac{(\eta_P \eta_m)}{w} \cdot \dot{Q}_D^{1.5} \times \frac{32}{0.95\sqrt{5\pi\rho C_p|-0.4T_{DS} - 120.2\ \text{K}|}} \quad \{\text{In district cooling}\} \tag{14}$$

On the other hand, while the average number of floors of buildings connected to the same district energy system, n increase the total length of piping decreases, but thermal energy to be transferred in each pipe increases. A direct relationship between the pumping power per piping length and the average number of floors has been developed. In Eq. (15), y and l are the constants depending on the district characteristics and size, climate, and building typology.

$$\frac{P_E}{L} \leqslant \frac{y}{\sqrt{n^l}} \tag{15}$$

After letting $L = L_{max}$ and solving related equations simultaneously, the following expression for the maximum allowable total pumping power, namely P_{Emax} is obtained.

$$P_{E\max} \leqslant \frac{y \times L_{\max}}{\sqrt{n^l}} \tag{16}$$

For city planners and architects, these equations allow them to optimize n, L, and P_E for minimum total CO_2 emissions, including avoidable emissions during the operation of the district energy system:

$$\sum CO_2 = CO_2 + \Delta CO_2 = \left(\frac{c_K}{n_T}\right) P_{E\max}\left(2 - \bar{\psi}_R\right) \leqslant \left(\frac{c_K}{n_T}\right) \frac{y \times L_{\max}}{\sqrt{n^l}}\left(2 - \bar{\psi}_R\right) \tag{17}$$

Eq. (17) introduces the primary metric of this study $\bar{\psi}_R$, which must be maximized for 5DE systems with minimum exergy destructions. Eq. (17) also shows that ΣCO_2 is a linear function of the circuit length. It may be presumed that by using multiple parallel circuits in (nn) number of shorter identical district lengths, L_i emissions may be reduced. This solution is possible only if total L_i is less than the length of a single large circuit, shown by Eq. (18), which brings another optimization dimension by an optimum number of parallel circuits.

$$\sum_{i=1}^{nn} L_i < L \tag{18}$$

Assuming a linear relation between ΔT and T_{DS}, the maximum allowable district distance from the plant also decreases. Therefore, 5DE systems must be shorter in heating because they rely on ultra-low temperatures. For example, L_{max} decreases by 1/1.54 when T_{DS} decreases from 345 K to 308 K. In cooling, L_{max} must also be shorter at higher supply temperatures. This condition is a trade-off between utilizing low exergy thermal sources and more infrastructural embodiments. Even if the finance is kept to be the dominant factor despite climate warming issues, there is a definite relationship between the average number of floors, n and the pay-back period, $Y(n)$:

$$Y(n) = Cn^{\left(l\left[\frac{m_p}{2}+1\right]-k\right)} \tag{19}$$

The coefficient m_p represents the effect of the pipe wall thickness on its pressure resistance according to diameter. Terms C, l, and k depend on the specifics of a district energy system. Then, Eq. (19) deduces the economics of the district energy system size, i.e., the degree of de-centralization versus centralization.

a. If $\left[\frac{m_p}{2}+1\right] - k > 0$, then the pay-back period increases with n,
b. If $\left[\frac{m_p}{2}+1\right] - k = 0$, then the pay-back period is independent of n,
c. If $\left[\frac{m_p}{2}+1\right] - k < 0$, then the pay-back period decreases with n.

Generally, case (a) applies, meaning that high-rise buildings must be avoided. Simply put, the city planners are faced with a very complicated problem about deciding the average number of floors in the buildings of a city because it affects the pay-back periods, CO_2 emissions responsibility thus the size and location of cogeneration plants.

4.5. The 2nd Law in Carnot cycle equivalency

Concerning non-thermal energy sources, virtual supply temperatures were defined in terms of the ideal Carnot cycle.

$$E_X = \varepsilon \cdot Q = \left(1 - \frac{T_{ref}}{T_f}\right) \cdot Q < Q \quad \{E_X < 1\} \tag{20}$$

Here, T_f is the source temperature in thermal systems. For non-thermal systems, Carnot cycle-equivalent virtual temperature is defined for different energy sources:

Table 2
Unit Exergy of Different Energy Sources. T_{ref} = 283 K (©2021 Kilkis, B.)

ENERGY SOURCE	Fuel (Source)		Application
	T_f [K]	ε_{sup} [kW/kW]	Efficiency*
Solar Energy at I_n = 700 W/m^2	550.6	0.486	0.50
Solar Energy at I_n = 1000 W/m^2	927.8	0.695	0.55
Wind Turbine Electricity at η_{WT} = 0.35	423.8	0.332	0.45
Wind Turbine Electricity at η_{WT} = 0.45	494.3	0.427	
Electrical Power (at the plug)	5778	0.951	0.50
Wave Energy (Mechanical Energy)	5778	0.951	0.60
Waste Heat at 90 °C (363 K)	363	0.220	0.60
Waste Heat at 30 °C (303 K)	303	0.066	0.40
Steam at 600 K (Condensing at constant 2 atm)	761	0.628	0.8
Steam Condensate at 120 °C	393	0.279	0.45
Geothermal Energy at 100 °C	373	0.241	0.50
Geothermal Steam (See above for steam)	760	0.627	0.8
Natural Gas**	2230	0.873	0.75
Biogas**	1600	0.823	0.60
Coal**	2000	0.858	0.70
Wood Pellet (size smaller than 13 mm)**	1100	0.743	0.60
LPG**	2240	0.874	0.60
Hydrogen Gas**	2400	0.882	0.85

* If proper utilization (s) made,
** Based on adiabatic flame temperature.

Solar

$$\varepsilon_{solar} = \frac{I_n \times 0.95}{1366} \tag{21}$$

$$T_{fsolar} = \frac{T_{ref}}{(1 - \varepsilon_{solar})} \tag{22}$$

If, I_n is 700 W/m^2, then ε_{solar} is 0.486 kW/kW, and the virtual T_{fsolar} at T_{ref} = 283 K (10 °C) is 550.6 K.

Wind Energy

$$T_{fWT} = \frac{T_{ref}}{(1 - 0.95\eta_{WT})} \tag{23}$$

$$\varepsilon_{WT} = \left(1 - \frac{T_{ref}}{T_{fWT}}\right) \tag{24}$$

Geothermal Steam

$$\varepsilon_{GS} \cong 0.00198(T_{GS} - 283K) \tag{25}$$

$$T_{fGS} = \frac{T_{ref}}{(1 - \varepsilon_{GS})} \tag{26}$$

The wide spectrum of different exergy values among energy sources and applications requires a new understanding of 'green' buildings in the era of new strategies to utilize renewable and waste energy sources against climate emergency. Eqs. (20)–(26) and Table 2 show that all energies (fuel) are not equal in their unit exergy. The variation is between 0.066 and 0.951, which is 135% concerning the arithmetic average of 0.657 kW/kW. The last column, which depends on the end-use, has less variance in typical applications in the field. The variance is only 21%, between 0.40 and 0.85, concerning the arithmetic average of 0.57. It must be noted that this table may be further improved to better guide the strategists in prioritizing the energy sources and matching application sets by rationing the world-energy supplies in terms of their types, unit exergy, and allocation to best practices in the field.

According to Fig. 1, the ratio of 65 % corresponding to the worldwide waste heat, which are <100 °C (373 K), has to be applied, while 21 % ratio is applied to sources above 300 °C (573 K). This table should also include an exergy destructions column and another column for ψ_R, for a complete exergy-based picture not only for the next-generation green facilities but also all sectors involved in the global warming effect. Even in its simple form, shown in Table 3, such an approach and understanding are not present in any current green facility program.

The exergy-levelized cost is a new metric to reveal the actual costs of solar panels:

$$ELC = \left(\frac{PC + EM \times W_p}{I_{test}A_p\left[\varepsilon_{supE}\eta_E + \varepsilon_{supH}\eta_H\right]}\right) = \left(\frac{1+k_E}{I_{test}A_p\psi_R}\right) PC \quad \{\text{Minimize}\} \tag{27}$$

s.t.: $\psi_R \geq 0.70$; $\eta_E \geq 0.15$; $k_E \leq 1$.

$$k_E = \frac{EM \times W_p}{PC} \quad \{\text{Embodiment Factor}\} \tag{28}$$

W_p is panel weight (kg), PC is in €. EM is in Euro/kg. ELC (€ $kW_{EX}^{-1}m^{-2}$) is defined at test conditions.

Eq. (27) may be further simplified by defining an exergy-leveling factor, LF, which adjusts the simple market cost of a solar system and therefore reveals the actual cost of the panel. For example, a PVT panel has a market price, which is twice as much as an FPC panel of the same dimensions, A_p, and designed for the same solar test conditions. Their k_E values are 1.3 and 0.7, respectively.

$$LF = \left(\frac{1+k_E}{I_{test}A_p\psi_R}\right) \tag{29}$$

Their ψ_R values are 0.75 and 0.30, respectively. Using Eq. (27), the ELC value of the PVT panel is only 54% of the FPC panel. This result shows that the 1st Law alone is not sufficient to rate different solar systems. As a second example, if a flat-plate collector supplies heat only (No power generation) for an open-circuit domestic use (DHW) between a supply temperature of 340 K and a return temperature of 290 K (freshwater supply), its ELC is about twenty-seven times the standard market price, PC. This result is the total cost of an FPC panel from environmental and value-adding potential points of view. A similar equation may also be derived for CO_2 embodiments, EM_{CO2}, and exergy destructions during operation at a given renewable ratio, R_X:

$$ELC_{CO_2} = \left(\frac{EM_{CO_2}(W_p) + 0.27(1-R_{EX})I_{test}A_p(1-\psi_R)}{I_{test}A_p\psi_R\left[\varepsilon_{supE}\eta_E + \varepsilon_{supH}\eta_H\right]}\right)\{kg\ CO_2/kW_{EXpeak}/m^2\} \tag{30}$$

Eq. (30) may be adapted for wind turbines and geothermal energy systems (see Table 3):

$$ELC_{CO_2} = \frac{4(1+k_E)TC}{\pi D_{WT}V^3_{wdesign}\left[\varepsilon_{supE}\eta_{wt}\eta_G\eta_{GB} + \eta_H\varepsilon_{supH}\right]} \quad \{\text{Wind Turbine.s.t. } \eta_{wt} < \eta_{BL}\} \tag{31}$$

$$ELC_{CO_2} = \frac{(1+k_E)GC_{total}}{P_g\left[\varepsilon_{supE}\eta_E + \eta_H\varepsilon_{supH}\eta_H\right]} \quad \{\text{Geothermal Energy.s.t. reservoir life}\} \tag{32}$$

$$\eta_I = \frac{Q_E}{Q_{SOLAR}} = \frac{Q_H}{Q_{SOLAR}} = 0.20 \ \{\text{Heat is utilized only between 365 K and 340 K to avoid Legionella Risk}\} \tag{33}$$

$$\eta_{IIPFPC} = \frac{Q_H(1-T_R/T_E)}{Q_{SOLAR}\varepsilon_{SOLAR} + 0.95 \times Q_{pump}} \tag{34}$$

$$\eta_{IIPV} = \frac{0.95 \times Q_{SOLAR} \times COP_{PV}}{Q_{SOLAR}\varepsilon_{SOLAR}} \tag{35}$$

$$COP_{PV} = \frac{Q_E}{Q_{SOLAR}} - ([1-\eta_{inv}]\eta_{PV}) = 0.2 - ([1-0.95] \times 0.20) = 0.19 \ \{\eta_{inv} = 0.05,\ \eta_{PV} = 0.20\} \tag{36}$$

$$COPE_{XPV} = 0.95 \times COP \tag{37}$$

$$COP_{FPC} = \frac{Q_H}{Q_{SOLAR} + Q_{pump}} = 200/1045 = 0.191 \tag{38}$$

$$COP_{FPC} \simeq \eta_{IIFPC} \tag{39}$$

$$\psi_R = 1 - \frac{\varepsilon_{des}}{\varepsilon_{sup}} \ \psi_R = \frac{\varepsilon_{dem}}{\varepsilon_{sup}} = \frac{\left(1-\frac{T_R}{T_E}\right)}{\varepsilon_{sup}} \ \{\text{ Major exergy destruction downstream}\} \tag{40}$$

5. Issues about green building certification programs

5.1. Insistence of using only the 1st Law

Today's green building certification programs are based on the 1st Law, dealing only with the quantity of energy. In the quest for total electrification in the built environment, part of the power in many countries continue to be generated by fossil fuels. In this respect, the 1st Law is opaque to the power generation background, shown in Fig. 15, which affects the climate crisis and health. Although green buildings are credited for renewable power utilization, it is not recognized that green power systems also have emissions responsibilities according to exergy destructions.

5.2. The green concept needs to extend from green buildings to green cities

A global SDEWES Index is already in place, which covers >100 major cities all over the world. This index also includes water management and emphasizes the importance of energy, environment, and water nexus in the interconnected conglomeration of buildings with other functions of the cities at large. Current certification

Table 3
Numerical Performance Comparison of PV and FPC Panels with Identical Solar Insolation Quantity. I_n = 700 W/m^2, ε_{solar} = 0.487 kW/kW, T_f = 552 K, T_E = 365 K, T_R = 340 K, T_{ref} = 83 K, Q_{SOLAR} = 1000 W, Q_E = Q_H = 200 W, ε_{dem} = 0.068 kW/kW and Q_{pump} = 45 W (For FPC).

CASES	Existing Green Metrics (1st Law)				Exergy-Based NewAdditional Metrics (2nd Law)						
	η_I Units	[–]	CO_2 kg CO_2/h	COP [–]	ε_{des} [kW/kW]	η_{II} [–]	ψ_R [–]	COP_{EX} [–]	ΔCO_2 kg CO_2/h	CO_2 kg CO_2/h	ΣCO_2 kg CO_2/h
Case 1: PV	0.20		0	0.19	0.225	0.37	0.54	0.180	+0.012	−0.1	−0.088*
Case 2: FPC	0.20		0	0.19	0.506	0.026	0.14	0.026	+0.05	−0.05	0

* Minus ΣCO_2 means the net carbon sequestration potential of the system.

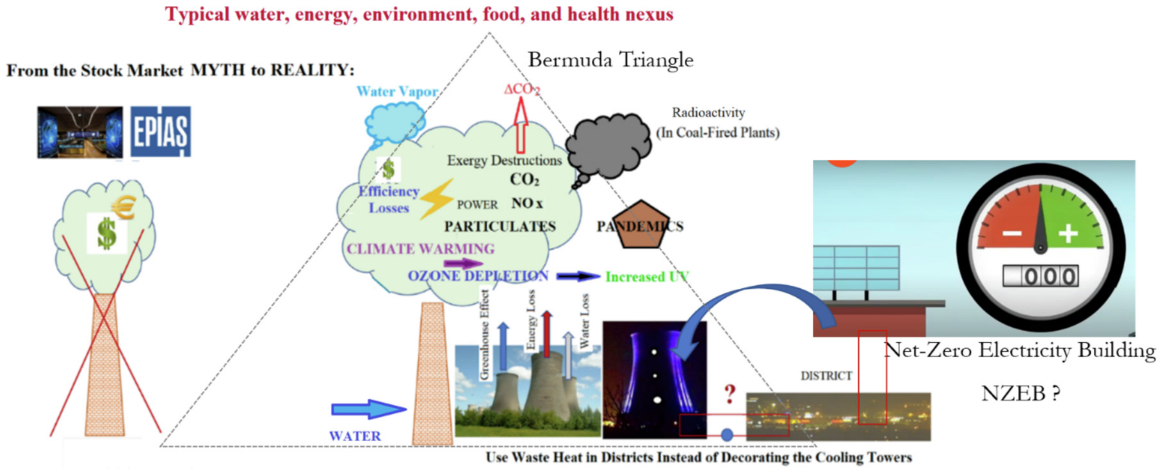

Fig. 15. The Dark Side of Electric Power in the Stock Market Traded as a Financial Commodity.

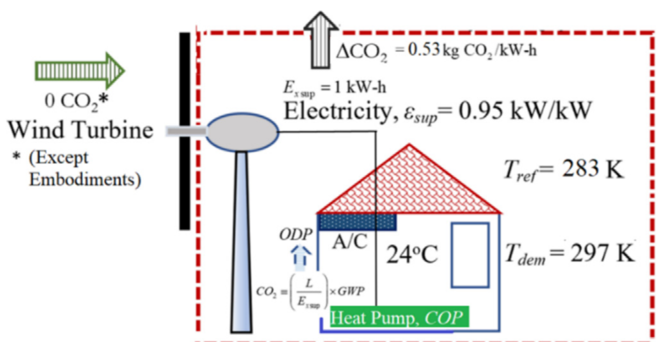

Fig. 16. Wind-to-Heating in a Chinese Project.

programs do not have such a nexus recognition yet (Fig. 15) and trade power as a simple financial commodity.

6. Bad practices

6.1. China: wind energy-to-heat

The Chinese government plans to reduce CO_2 emissions in rural areas of cold climates by replacing coal stoves and boilers with wind turbines. Exergy destruction between wind electricity and the exergy of the heating demand causes ΔCO_2. If a heat pump is used, then the refrigerant leakage also has a ΔCO_2-equivalent ozone depletion effect. For each kW-h of wind electricity supply, the emission responsibility is based on R32 refrigerant with a *GWP* of 677, and an assumed leakage rate, *LR* of 1.7×10^{-4} kg/h, is calculated as follows:

$$\sum CO_2 = 0.63 \times 1\ \text{kW - h} \times (1-\psi_R) + (LR/\text{kW - h})GWP = 0.65\ \text{kg } CO_2/\text{kW - h} \qquad (41)$$

$$\psi_R = (1 - 283\ \text{K}/297\ \text{K})/(0.95/COP)0.15\ \{COP = 3 \text{ for heating in cold climates}\} \qquad (42)$$

For a lignite stove with ε_{sup} of 0.8 kW/kW and efficiency of 0.35, ΣCO_2 is 0.26 kg CO_2/kW-h. Therefore, although the 1st Law indicates almost zero CO_2 responsibility with $COP = 3$ ($COP_{EX} = 0.14$), the 2nd Law shows that the nearly-avoidable emissions responsibility is 2.5 times more without introducing additional useful work upstream like power.

6.2. Istanbul grand airport (IGA)

Istanbul Airport terminal building received LEED Gold certification in 2020 with two points for green energy provided by a wind power vendor nearby the airport. Nevertheless, most green power is used to cool the building with conventional chillers with low *COP*, leading to a considerable amount of exergy destruction (Fig. 17). The 2nd Law considerations in this paper show how

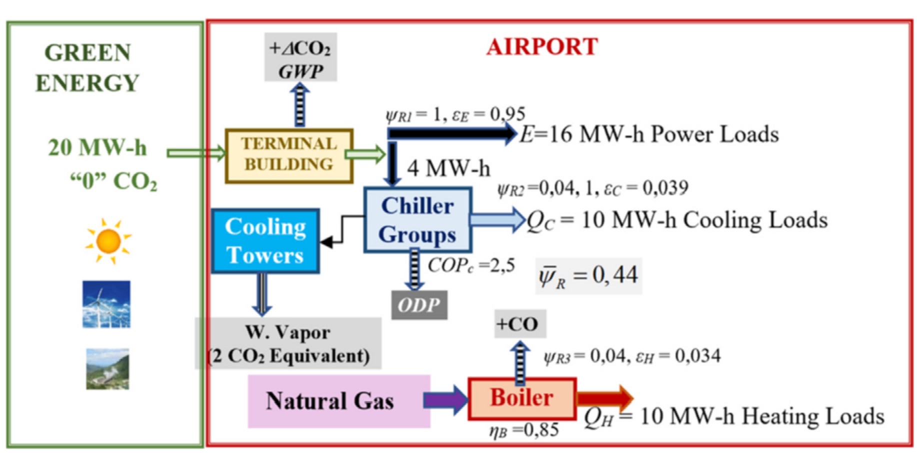

Fig. 17. Energy Enters Green but Partially Turns Grey in the Green Terminal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and where and how green energy is used must be questioned. Fig. 18 shows that reducing green power and adding a cogeneration system with natural gas may be greener.

6.3. Labyrinth preconditioning of indoor fresh air

They are credit-worthy applications in many certification programs, especially during 100 % fresh air requirements against pandemic risk indoors. The electric power exergy input for the air-circulating fan(s) in the labyrinth must be much less than the thermal power exergy (supply/extraction) for a positive unit exergy gain. If, for example, the winter outdoor temperature t_{out} is −15 °C, and the preheated supply temperature of outdoor air, t_{in} is +2 °C, then for each kW of heat (1 kW_H), the fan power must be <0.065 kW_E (see Fig. 19).

$$\frac{P_{FAN}}{1\ kW_H} << \frac{\varepsilon_H}{\varepsilon_E} = \frac{\left|1-\frac{273.15-15}{273.15+2}\right|}{0.95} = \frac{0.062}{0.95} < 0.065\ kW_E/kW_H \quad (43)$$

$$P_{FAN} < \left|1-\frac{T_{out}}{T_{in}}\right|/0.95 \quad (44)$$

If P_{FAN} is 0.25 kW_E, Eq. (44) is not satisfied, and exergy is destroyed between the power and heat:

$$E_{Xdes} \approx |\varepsilon_E \times 0.25\ kW_E - \varepsilon_H \times 1\ kW_H| = 0.95 \times 0.25 - 0.062 = 0.175\ kW \quad (45)$$

6.4. The Dutch green district with solar prosumers

The Dutch Consortium Project, Dezonnet with TU Delft, claims that it makes a neighborhood free of natural gas without using any outside heat and saves a considerable amount of CO_2 emissions. Prosumers have PVT systems in a community in Overveen in North Holland. The main components of the district energy system are a large aquifer type of central seasonal thermal energy storage system (ATES), which is interconnected to the prosumers through district piping, which requires a considerable amount of electrical power for pumping. If the flow rates, pipe diameters, and district distances are not carefully optimized, the exergy demand for electricity may exceed the exergy supply, which is in the form of low-temperature (LT) heat to the prosumers or received from the prosumers. Heat pumps need to have a *COP* of greater than eight in heating and ten in cooling to have a positive exergy gain. Furthermore, if net grid electricity is demanded from time to time, direct CO_2 emissions at the power plants will occur, depending upon the fossil fuel and renewable energy mix in the national energy budget, which brings the Legionella problem. AC power requires AC-to-DC inverter(s) downstream PVT.

$$\sum CO_2 = 0.27E_{xsup}(1-0.12) + (L/E_{xsup}) \times GWP = (0.23 + 0.093**) = 0.33\ kg\ CO_2/kW\text{ - }h \neq 0\ \{\text{Exergy}\} \quad (51)$$

Based on R32 HFC refrigerant leakage, *L* of 1.7 × 10^{-4} kg in one hour and a *GWP* of 550. *ODP* = 0, *ALT* = 10 years (Estimate). Although *ODP* is zero, refrigerant leakage results in a CO_2-equivalent greenhouse effect per kW-h of exergy. To convert it to per kW-h of energy, divide it by the ε_{sup} = 0.0346 kW/kW, which means 9.5 kg CO_2/kW-h heat. If in summer the heat pump is used for cooling at 6.5 kW-h, then it is about 62 kg CO_2. This unseen amount is half of an SUV emission from its tailpipe:

$$ODI = \frac{0.1GWP^{0.03}}{(1-ODP)} \times \left(\frac{ALT}{1}\right)^{0.01} = 0.124$$

ATES has a direct CO_2 responsibility due to heat losses (gains in cooling) to/from the ambient ground throughout the year and a nearly-avoidable CO_2, namely ΔCO_2, due to temperature drops (gains) in its internal heat exchangers.

$$CO_2 = \left(\frac{0.2}{0.85}\right)\frac{\int_{t=0}^{t=5280} kA|T_g(t)-T_m(t)|dt}{5280 \times 1\ kW} \simeq 0.235\frac{kA|\bar{T}_g-\bar{T}_m|5280}{5280 \times 1\ kW} \simeq 0.235kA|\bar{T}_g-\bar{T}_m| \quad (52)$$

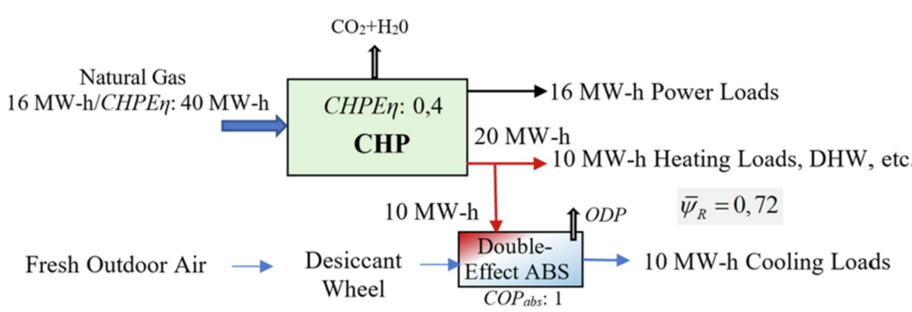

Fig. 18. Energy Enters Grey but Turns Greener in the Same Terminal Building.

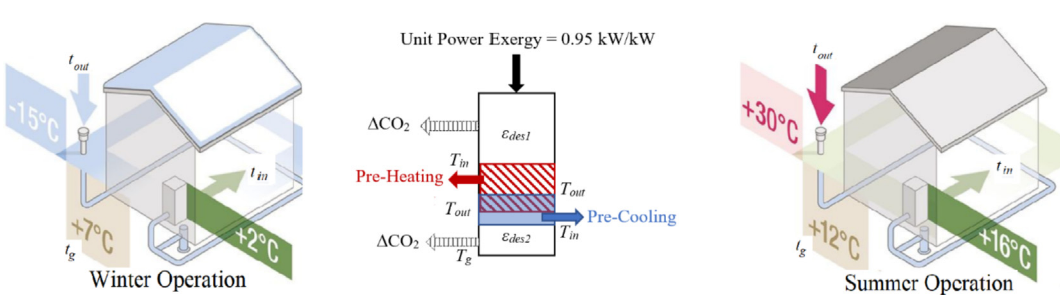

Fig. 19. A Labyrinth Type of Fresh Air Preheating in Winter and Precooling in Summer.

In a further step, let the ATES geometry be a box shape with a square bottom with sides X and height, $h = aX$. Any kW-h of heat charged or extracted incrementally increases (decreases) the average tank temperature by ΔT_m:

$$\Delta T_m = \frac{1\ \text{kW - h}}{\rho V C_p \Delta T_m} \tag{53}$$

Is related to the base area of box-shaped (Prismatic) ATES, A:

$$V = \frac{aX^3}{2X^2 + 4aX^2} \tag{54}$$

It must be noted that the volume per minimum surface area is at $a = 1$, i.e., $h = X$. Best geometric solution is a spherical tank, with a diameter X , if technically and economically feasible. Assuming that T_g stays approximately the same,

$$CO_2 \simeq 0.235k\left|A\bar{T}_g - \frac{2(1+4a)}{\rho C_p aX}\right| \quad \{\text{Prismatic},\ \ a > 0\} \tag{55}$$

If the geometry is close to a cylinder with internal wall segments, then Eq. (55) becomes:

$$CO_2 \simeq 0.235k\left|A\bar{T}_g - \frac{2(1+a)}{\rho C_p aR}\right| \quad \{\text{Cylindrical},\ a > 0\} \tag{56}$$

Here, k is the overall thermal conduction coefficient of the tank walls with insulation. A is the total external surface area of the tank. Furthermore, the tank material and construction have large amounts of embodied energy, exergy, and CO_2 emissions. Their arrangement has no information about DHW in their report against Legionella risk. Local biogas production should also be considered. Embodiments, like CO_2 embodiments, were not considered in their project.

7. Advanced green certification model

The new model developed during this study includes the following metrics in a punch-card format (see Fig. 20).

7.1. Punch card

- Building- Specific Metrics
- For example, airports and hospitals have different pandemic risks since hospitals have mostly local patients and staff, while international airports are a meeting and breeding point of pandemics.
- General Metrics
  - o Pandemic resistance

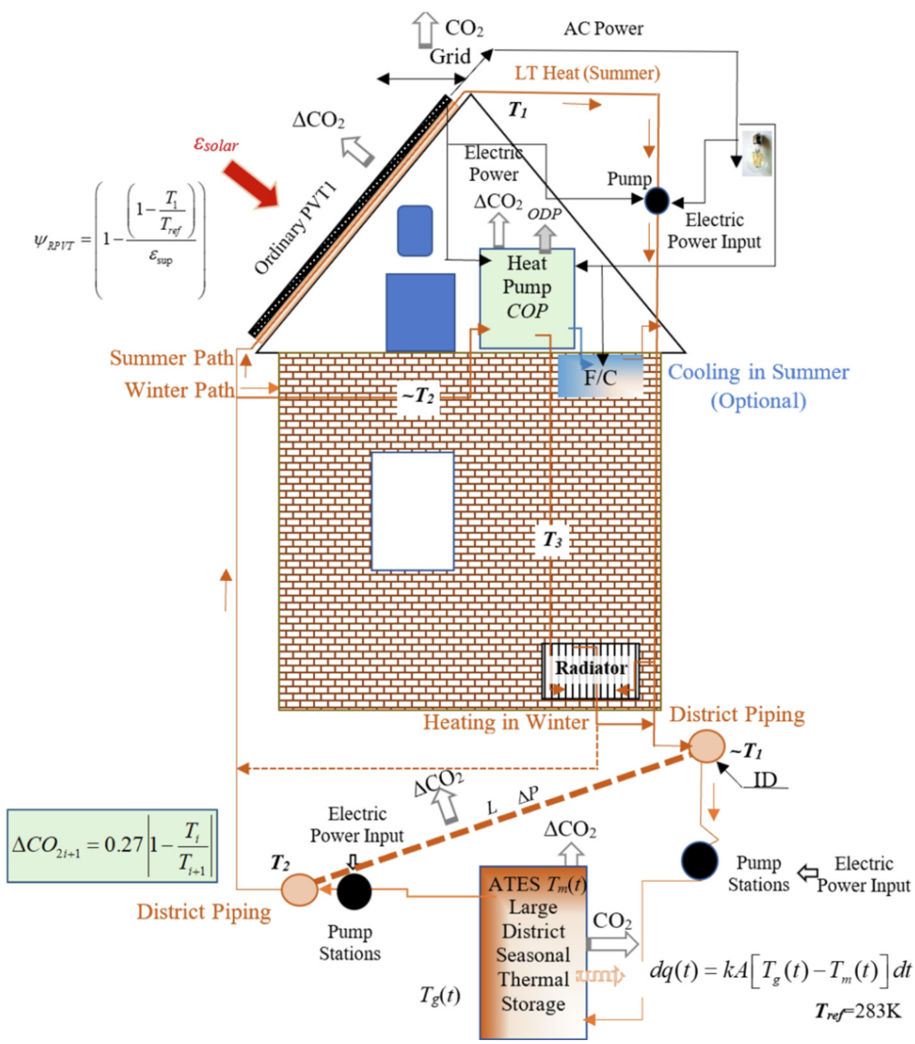

Fig. 20. Central District Thermal Storage, Heat Pump, And PVT Panels. c Is a Constant For Pressure Drop Per Unit District Length L. η_{pm} is The Combined Pump and Motor Efficiency *Note:* Temperature loss or gain at Low-temperature conditions from or to the district pipes and ancillaries between the ambient or ground are neglected, assuming that optimum insulation is applied.

- o Radon free environment
- o Earthquake resistance
- o Tsunami adaptive buildings (Critical countries like Holland)
- o Proximity to high 5G transmitters, radar stations, high voltage power lines, etc.
- o The exergy-based human comfort index, PMV_{EX}
- o Sound levels
- o Upstream energy source breakdown → Radioactive material, cooling towers, concerning greenhouse effect
- o Upstream global decarbonization potential metric
- o Downstream wastes, utilization of waste heat, etc.
- o Radiation-free materials (not only VOC)
- o minimum ΔCO_2, CO_2, ΠCO_2
- o *ODP* → UVB, *GWP,* and *ODI*
- o *RUE, RUEX*
- o New nZCB definitions, nZEXAP, nZEXHB, extended to nZCFarm, etc.
- o ψ_R and all other new metrics provided in this paper
- o Proximity to high-voltage transmission lines
- o Proximity to nuclear, coal, and lignite plants radiation
- o Proximity to H_2S gas-emitting geothermal plants, renewable, and waste energy sources
- o Tree cutting or planting
- o Decoupling of latent and sensible loads
- o Type of refrigerants and compressors used
- o Use of low-exergy heating and cooling equipment

7.2. Holistic view

Buildings are overwhelmed by the quadrilemma chain with several constraints that change with location, climate, and country, such that any certification program must be adaptive to local conditions and constraints and responsive to them. For example, ' 'Istanbul's air pollution is very high compared to cities in the EU. How should effective filtering the outdoor air be? A building in Istanbul needs much filtering. Therefore, energy use, exergy rationality, fuel consumption credit points must be adaptive. Therefore, metrics must be location sensitive, and four levels of metrication must be recognized: 1- Building Level, 2- District Level, 3- City Level, 4- Global Level (see Fig. 21).

7.3. Safe distancing inside the green buildings

The mobility of people, especially in large buildings like air terminals, is three-dimensional instead of a linear assumption. Large green buildings must monitor them to maintain the minimum distance of occupants under different dynamic conditions in terms of L_{min} instead of defining fixed social distancing criteria like 1.5 m. So instead of social distancing, socially safe areas, defined by the new term *SA,* must be used in green building ratings for hygiene and safety (Fig. 22). *Here, n* is the instant number of persons, and n_o is the maximum allowable number of people.

$$SA = \left(SM + 2A + \sqrt{2}TM\right)^2 \tag{57}$$

$$SM = A\left(1 + [n/n_o]^c\right) \tag{58}$$

$$A = A_0(1 + n^d) \tag{59}$$

Fig. 23 further shows that the ceiling height is also important, adding the third dimension for architects and civil engineers, besides mechanical engineers who design the HVAC systems, like airport terminals.

7.4. Exergy-Based human comfort

Concerning HVAC system design, the indoor operative temperature must be used on the human exergy diagram, which is especially important in metro stations, airports, large markets, especially in rush hours. Human exergy loss must be minimized during their transit through such places against maintaining their resistance to viruses under stress. A sample diagram is given in Fig. 24 [37]. Radiant heating and cooling are one of the primary methods to establish the minimum exergy loss requirements. Bangkong air terminal building is a prime example of radiant panel systems in large buildings [38]. Therefore, Eq. (60) must be a reference for the next-generation green certification programs for maximum human comfort. Decoupling of the sensible and latent loads in a green building is not only important for exergy-based PMV (Predicted mean vote) but also from the energy point of view. Especially within the pandemic era, most of the buildings are required to have 100% fresh air. Conventional HVAC systems (*PR* = 0) use the same ductwork for simultaneously satisfying sensible and latent loads together, which increase the fan power, duct size and make the controls difficult. A high *PR* value for next-generation green programs means an exergy-rational load decoupling.

$$PMV_{EX} = PMV + a|0,6 - PR|^2 + b\varepsilon_H + c\left(IAQ_{ref}/IAQ\right) \leqslant 0,6 \tag{60}$$

7.5. Deforestation

Trees and plantations are important factors in sequestering CO_2 emissions in the atmosphere. Therefore, green metrics must rate deforestation also. Eqs. (61) and (62) should establish new penalizing metrics. *DF* is the number of cut trees, *s* is the average annual CO_2 sequestration potential [kg CO_2/a], A_F is the deforested area [m^2]. E_T is the annual energy consumption of the facility [kW-h/a]. A_T is the total footage area of the facility [m^2].

$$OR = \frac{(DF \times s)/A_F}{(\sum CO_2 \times E_T)/A_T} \quad \{< 0.05\} \tag{61}$$

Fig. 21. Four Levels of Sustainably Green Environment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

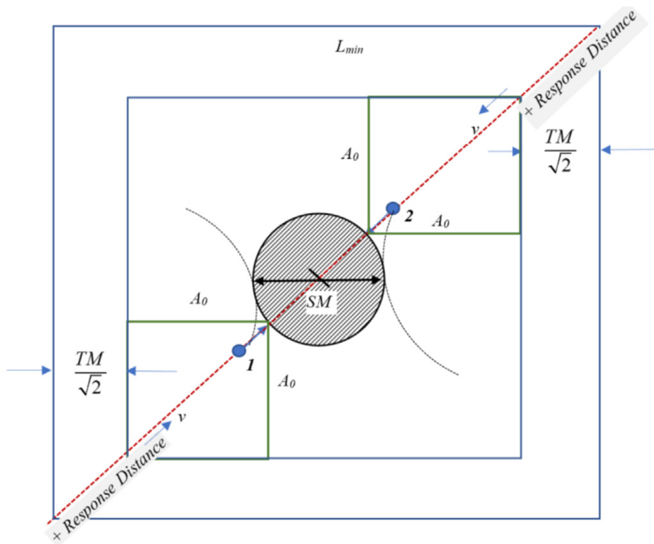

Fig. 22. Minimum Dynamic Safe Area Method (Drawn by the Authors).

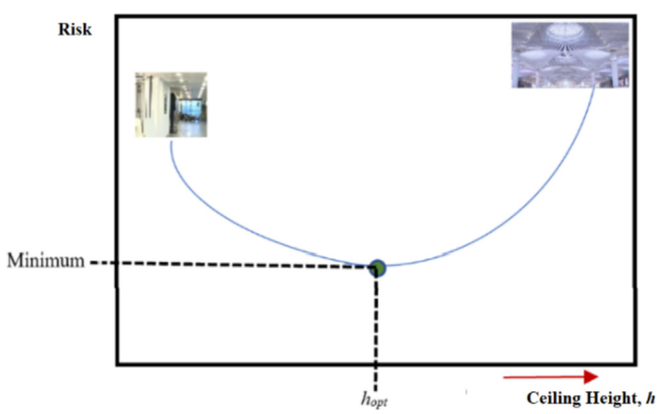

Fig. 23. Optimum Ceiling Height Against Virus Spread (Drawn by the Authors).

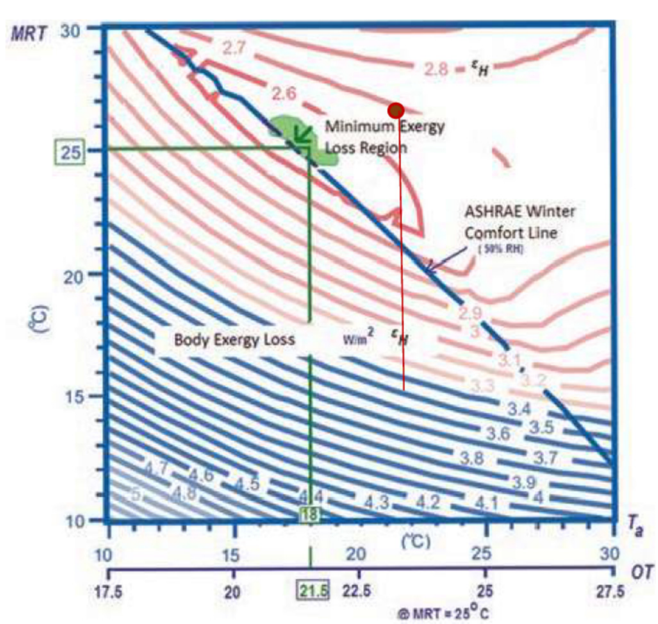

Fig. 24. Exergy-Based Comfort Diagram [37].

The following equation gives the minimum number of young trees to be planted ($m \sim 1{,}8$).

$$N = \left([100/0.01 + OR]^{1/m} + 5\right) \times 1.2 \quad (62)$$

7.6. Indoor air quality

For very large buildings, Table 4 has been developed, with stricter measures for indoor air quality, HO.

$$HO = [CO + (NO + NO_2) + P_{2,5} + P_{10}]/500 < 1 \quad (63)$$

This study has developed twenty-three next-level green building compound rating metrics presented in Table 5. Seventeen metrics are missing in the current green certification programs, and the rest satisfy partly. For example, deforestation factor, OR, ozone depletion index, ODI, the prime metric ψ_R are neither used nor referenced, which are among the most influential metrics directly affecting global warming.

8. Common statements that are thought to be true

8.1. It is not important how green energy is being used in the facilities.

It is not a valid assumption, as presented in Figs. 16 and 17.

8.2. Condensing boilers are highly environmental.

As seen in Fig. 25, this condition only requires that the boiler intake is closest to the dew point. Coefficient Z in Eq. (64) is dependent on the boiler efficiency change due to intake temperature, total efficiency supplied by the electric power, environmental baseline, and required temperatures. $c_{ünd}$ is the CO_2 content calculated according to the fuel's higher heating value. If the boiler intake temperature is lowered for boiler efficiency to rise, as shown above for aluminum and steel radiators, the heaters must be enlarged, so the CO_2 emissions become much higher.

$$CO_2 = \frac{c_{ünd}}{Z} \quad (64)$$

8.3. Cogeneration and trigeneration systems are very expensive.

Even though dependent on imports, the foreign currency paid for imported natural gas repays in about 2 or 3 years.

8.4. The 1st Law is sufficient for design and operations.

On the contrary, the advantages considering the greater usage of renewable and excess energy resources can only be understood by the 2nd Law.

Table 4
New IAQ Limits for Large Green Establishments.

Particle	New Upper Limits
CO	<310 μg/m³
$P_{2,5}$	<8 μg/m³
P_{10}	<20 μg/m³
($NO + NO_2$)	<75 μg/m³
CO_2	<120 ppm
HO	<1 (Eq. (60))

Table 5
Next-level Green Establishment Metrics.

Metric		Explanation	Requirement	Existing Certificates
ψ_R		Rational Exergy Management Efficiency	> 0.70	x
η		1st Law Efficiency	> 0.75	Partly satisfies
η_{II}		2nd Law Efficiency	> 0.50	x
PES_R		Exergy-Based Fossil Fuel Savings Ratio	>50%	x
PER		Primary Energy Ratio, $COP \times \eta$	>2	Partly satisfies
SF	Heating	Peak Load Shaving Factor	>0,3	x
	Cooling		>0,4	
DF		Diversity Factor	<0,2	x
EDR		CO_2 Sequestration Ratio	>0,70	Indirectly satisfies
SEO		Renewable Energy Ratio	>0,50	Partly satisfies
$MREX$		Exergy-Levelized Humidity Control	$MREX$ > 3,5	x
OR		Deforestation Factor	<0,05	Partly satisfies
HO		Hygiene Ratio	<1	x
PMV_{EX}		Exergy-Levelized Thermal Sensation	≤0,6	x
IAQ/IAQ_{ref}		Indoor Air Quality Index	≥0,9	x
S		Number of visitors per exergy spending	>0,15 [kW-h/visitor]	x
ε_H		Exergy-Comfort Index	≤2,5 W/m^2	x
$\Delta CO_2/\Sigma\, CO_2$		Ratio of CO_2 emission components	<0,40	x
ODI		Compound Ozone-Depletion Index	<0,05	x
CWI		Global Warming Index $CWI = ODI/\psi_R$	<0,07	x
GAR		Exergy ratio spent in transit and residence	0,01	x
SA		Smallest Social Area Permitted	SA > 20 m^2/person]	Partly satisfies
SAD		Real-time Control of SA	YES/NO	x
PR		Decoupling ratio of sensible to latent Loads	>0.3	x

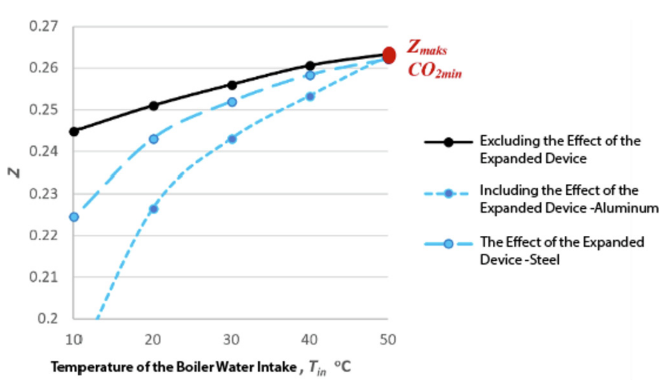

Fig. 25. Change of Coefficient (Z) According to the Boiler Water Temperature Intake [39].

8.5. Heat pumps are always environment-friendly.

This statement must be subjected to the new rating parameter HPF given in Eq. (65), which must be maximized for minimum ΔCO_2 emissions responsibility. HPF is an important metric to indicate ΔCO_2 and is a function of COP, which is inversely proportional to the supply temperature required by a thermal application T_{sup}. On the other hand, the exergy supplied by the heat pump, ε_{sup} at the same operating conditions, increases with T_{sup}. Current certification programs do not address these issues. The term (h) is 0.95/COP.

$$HPF = \left(\frac{COP}{0.95}\right) \times \varepsilon_{\mathrm{sup}} = \frac{1}{h}\left(1 - \frac{T_{ret}}{T_{\mathrm{sup}}}\right) \;\{\text{Maximize}\} \tag{65}$$

$$COP = a + b\left(\frac{\Delta T_o}{n}\right)^{-1} \tag{66}$$

$$\Delta CO_2 = \left(\frac{0.63}{h}\right)(1 - HPF) \;\{\text{Minimize}\}, \tag{67}$$

which may be satisfied by Eqs. (81) and (82).

$$T_{\mathrm{sup}} = \sqrt{\left(\frac{a}{b} + T_K\right) T_K} \;\{\text{Optimum value}\} \tag{68}$$

$$T_{ret} = T_{\mathrm{sup}}\left(\frac{a}{2b}\right) \;\{\text{Optimum temperature drop}\} \tag{69}$$

Future certification programs, should seek a maximum for the exergy-based COP, namely COP_{EXn} [6]:

$$COP_{EXn} = \left[a + b\left(\frac{n}{(3.8 + 1.2n)}\right)\right] \times \left(1 - \frac{T_{out}}{(T_{out} + 3.8 + 1.2n)}\right) \;\{\text{Maximize}\} \tag{70}$$

8.6. Air-to-air heat recovery systems are very efficient and economical.

Air-to-air heat recovery (in heating) or heat rejection (in cooling) may be energy efficient by the 1st Law but exergy inefficient by the 2nd Law, thus responsible for ΔCO_2 emissions. See Section 4.3.

8.7. Wind and solar power plants can be constructed in any suitable location

Federal Aviation Administration (FAA) has placed restrictions on constructing wind and solar energy systems near large buildings like airports. For example, relocation of the existing twelve wind turbines, each having a capacity of 2 MW electricity near the took six months, and the loss of energy was about 26 $\times$ 10^6 kW-h, corresponding to 10,000 tons of CO_2 emissions (based on a natural gas thermal power plant with the efficiency of 0.52). These adverse effects also need to be considered in certification programs. It must also be recognized that the global temperature increases by 0.256 $\times$ 10^{-13} $\times$ 1K for every kW-h of destroyed exergy [40].

It is expected that this paper will establish a new pillar for the near future for greener buildings. In this respect, some of the exergy-based metrics presented in this paper were adopted by the Turkish Green Building Certification Program, developed by the Turkish Standardization Institute (TSE) [41]. For example, the supply temperature demand is rated based on the low-exergy building status, and grade points are given accordingly. The LEED Platinum Office Building in Ankara was designed and built with exergy-based electro-thermal controls for maximum exergy efficiency [42]. This building is the first building equipped with such a control algorithm that can parent existing control systems.

9. Results and discussion

This paper introduced an exergetic approach and a new understanding of the holistic performance of buildings in terms of sustainability and decarbonization by taking into account the exergy mismatches among supply and demand points, leading to avoidable yet unaccounted for CO_2 emissions responsibilities. While buildings consume almost 40% of energy worldwide and occupants spend more time indoors due to permanent lifestyle changes due to the COVID-19 pandemic, constructively sustainable and more realistic strategies must start from the buildings. At this point, the green building definitions must be re-examined and upgraded to an exergy basis. For example, a net-zero prosumer building in a district energy system may not be a net-zero exergy building if the thermal exergy exchange has a surplus or deficit between the building and the district in terms of temperatures which only the 2nd Law can reveal.

The analyses presented in this paper have shown that green energy input to a so-called green building may not be so green depending upon where and how this green energy is consumed in the building. If electric power is consumed in a green building for electric-resistance heating, even if roof-top PV panels generate the electric power, this building may not qualify for zero-energy building because high exergy of electric power is destroyed by much lower-exergy heating demand. Such apparent nuances play a very important role in the real performance of green buildings, as exemplified in this paper.

A previous study of Kilkis [43] has shown that ozone depletion potential and global warming potential are directly related, as explained in this paper. The combined effect of *ODP* and *GWP* also indicates the presence of the global ΔCO_2 term. On the other hand, this study is particularly important for timely and sustainably reaching the Paris agreement goals. Fig. 26 shows three scenarios, including the business-as-usual one [19]. Even if advanced carbon capture and storage technologies are implemented, the result will be far from the Paris agreement goals. This study has concluded that the unaccounted root causes of CO_2 emissions comprise about 80% of the known causes. It means that at 45 % of a new window of opportunity is available for decarbonization by reducing the exergy destructions. Ideally, if a 40% reduction is achieved until 2050, the CO_2 concentration may reduce from 450 ppm to 270 ppm. This result coincides with the Paris Agreement goal of 280 ppm. This

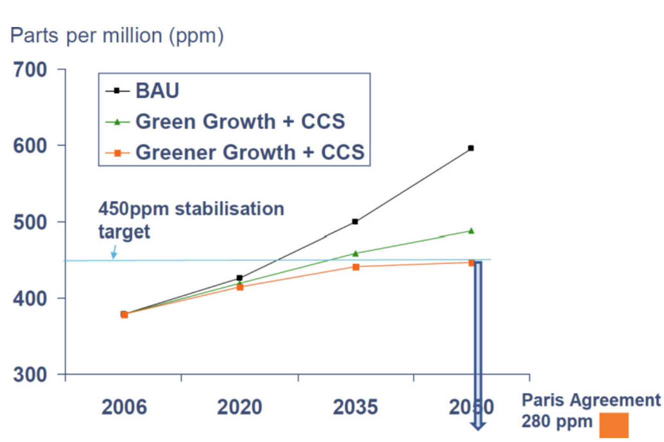

Fig. 26. Atmospheric CO_2 Concentration Predictions for Three Scenarios and Exergy. From: [19].

promisingly very strong and sustainable tool presented in this study represents the prime novelty of the paper.

During the COP26 meeting in Glasgow, fossil fuel lobbyists were able to downsize the global warming problem to simply ending only "inefficient" fossil fuel subsidies, as if there exist efficient and inefficient fuels in the energy stock. It is the most recent example of how deliberate or un-deliberate misconceptions prevail in the energy and building politics and the sector and reflects them to the current green building definitions. If there is an 'inefficient fuel in the sector, then how a green building using that fuel is going to be rated? There is not and may not be such a metric. Efficiency and rationality terms belong to how we rationally utilize or simply use and waste energy sources. There is no inefficient efficient fuel but high exergy and low exergy fuel, as depicted in Table 2.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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