Kilkis, B. 2022. Exergy-Rational Utilization of Solar Energy with Advanced PVT Systems and Heat Pipe Technology In 100%-Renewable Cities, ECOCITY21, Delft, the Netherlands, Paper Number 73, ECOCITY21, Delft, the Netherlands.

EXERGY-RATIONAL UTILIZATION OF SOLAR ENERGY WITH ADVANCED PVT SYSTEMS AND HEAT PIPE TECHNOLOGY IN 100%-RENEWABLE CITIES

Birol Kilkis,
OSTIM Technical University and Polar Technology, Ankara Turkey
birolkilkis@hotmail.com

Abstract

This paper responds to the EU goals of decarbonization with solar energy leading to fifth-generation district energy systems (5DE). The dilemma of low-exergy (low-temperature) district heating systems with renewable and waste thermal sources and the temperature-incompatibility of the current comfort heating equipment demanding higher supply temperatures is addressed. Until innovative, low-exergy equipment and higher-exergy solar photo-voltaic-heat systems are developed, various methods of optimum temperature peaking and existing equipment oversizing are presented. Central temperature peaking at the plant site and the individual prosumer buildings are compared. A case study is presented, which involves an individually optimized solar prosumer building with an optimum mix of heat pump oversizing and commercial radiator oversizing. Results show that CO_2 emissions responsibility-based optimum mix compared to economy-based optimum mix reduces the responsibility by 30%. This analysis was repeated by cascading two smaller heat pumps instead of a larger one to increase the overall *COP*. This change further improved the solution by 4% points. Results have also been compared to a modified case where cascaded heat pumps are coupled with low-exergy heat pipe radiators. This coupling resulted in much more improvement by an additional 52% points. The paper concludes that the key is low-exergy heating and cooling equipment. Then the fifth-generation district energy systems with supply temperatures as low as 320 K (47°C) and return temperatures as low as 300 K (27°C) will be possible with renewable and waste energy sources if the one-way distance between the plant and the district is not more than 1.6×10^{-5} km/kW times the thermal capacity of the district raised to a power of 1.5.

Keywords: Solar energy, wind energy, solar prosumer building, fifth-generation district heating, heat-pipe radiator, solar PV, FPC, and PVT, temperature peaking, equipment oversizing

1. Introduction

EU countries have developed roadmaps about 100% renewable energy utilization (100%RHC) and total electrification with renewable energy sources for building heating and cooling services using heat pumps. Based on the First Law of Thermodynamics, it is claimed that heat pumps running on 100% renewable electricity are not responsible for CO_2 emissions [1]. According to the Second Law of Thermodynamics, this is not the case because the 1st Law does not recognize that energy sources have different qualities (Exergy) regarding the large exergy mismatch between high-exergy electric power and low-exergy thermal power generated. Exergy is the useful work potential of a given quantity or energy flow. Especially with low-temperature systems, the quality of a given renewable energy source becomes particularly important.

1.1. Quality of Renewable Energy.

Electricity, whether generated from renewable energy sources or fossil fuels, has high exergy of 0.95 kW/W, which means that 95% of the energy quantity may be utilized in a wide range of useful applications besides heating or cooling. Exergy is defined by the ideal Carnot Cycle [2, 3]:

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

Here, T_{ref} is the reference environment temperature, and T_{sup} is the supply temperature in a district heating system. For example, 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, exergy will be only 0.115 of the heat supplied. Because heat pumps use electrical power, their coefficient of performance, *COP,* must be sufficiently high to match the electrical power exergy and the thermal exergy of the heat supplied:

$COP \geq 0.95 / 0.115 = 8.3$

If *COP* is less than 8.3, part of the electrical power exergy will be irreversibly destroyed, which has to be offset by someone, somewhere, sometimes by some type of fuels, causing additional CO_2 emissions responsibility. This emission is called nearly-avoidable emissions, ΔCO_2, because it may be largely avoided by minimizing the exergy destructions. On the contrary, if only the 1st Law was considered, any *COP* greater than one would be acceptable as a green application as long as renewable energy systems drive it.

1.2. Wide Availability of Low-Exergy Heat Sources

Low-temperature renewable and waste heat sources from different sectors below 100°C are abundant worldwide, corresponding to 63% of all the available waste heat sources. Unit exergy, ε of any waste heat below 100°C may be quite low (ε < 0.24 kW/kW at a source temperature of 100°C and a reference temperature of 283 K). About 50% of them have temperatures below 50°C. However, this is not a critical problem. Instead, today's major problem is the significant mismatch between the low Carnot exergy of the widely available low-temperature sources and the existing indoor heating equipment.

1.3. The Conflict Between the Existing Building Stock and Low-Temperature Heating

In many EU countries, half of the residential stock comprises buildings built before 1970, when the first thermal efficiency regulations were not in place yet [4]. Most of these buildings are energy-inefficient; despite some thermal insulation retrofits, their thermal loads are high. They run on old heating equipment like steel or even cast-iron radiators or natural-convection coils, which were designed for high supply temperatures. Therefore, a significant conflict exists between the many old buildings that demand high supply temperatures and the new EU roadmap of utilizing low-temperature thermal sources. Old hydronic heating equipment was designed for at least 70°C of supply design temperature (T_{eq}). EU is moving towards ultra-low temperature district energy systems, namely the Fifth-Generation DE (5DE) systems supplying temperatures as low as 35°C (T_{sup}) [5, 6]. 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 [7]. They argued that adding passive building systems for better retaining solar gains and other internal sources with continuous but lower thermostat settings shave off the peak loads and somehow enhances the utilization of low-temperature heat supplies. They further considered floor heating, wall heating, oversized radiators and convectors, and air heating.

The potential impacts of low-temperature heating from the buildings' perspective regarding 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 [8]. For public understanding and acceptance, they termed the low-exergy (Temperature) energy as `low valued` energy. They overviewed the impact of low-temperature supply on heating equipment for several types, including radiant floor and wall panels and 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 accomplished by innovative equipment and oversizing the existing equipment, except noting that heat pump *COP* values may increase due to reduced temperature deficit between the supply and demand. When the low-temperature source is provided at T_{sup}, over-insulation of the old buildings may reduce the deficit. 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. With over-insulation the building heat loads may be decreased, reducing the supply temperature requirement of the equipment, T_{eq} to T'_{eq}. 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 Equation 2 [9]. $T^{`}_{eq}$ is the supply temperature required by the heating equipment after optimally oversizing it to minimize 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 [10, 11].

$$\psi_R = \frac{\varepsilon_{dem}}{\varepsilon_{\sup}} = \frac{\left(1-\dfrac{T_{ref}}{T_a}\right)}{\left(1-\dfrac{T_{ref}}{T_{\sup}}\right)+\left(1-\dfrac{T_{\sup}}{T^{`}_{eq}}\right)} \qquad \{\text{Maximize}\} \qquad (2)$$

1.4. Centralized or De-centralized Peaking

Temperature peaking may be applied either at the central plant (Centralized) or at the district prosumers at an individual building level (Decentralized). A third option may be a hybrid of them. Figures 2 and 3 show the basics of these two alternatives. Each alternative has advantages and disadvantages. The centralized system houses large and preferably cascaded heat pumps in tandem for higher *COP* values for heating and cooling. The advantages are centrally manageable thermal energy storage, savings from grid losses corresponding to power transmission to the district to satisfy individual heat pumps there, easier and better maintenance, proximity to renewable energy systems, and the ability to centrally utilize district wastes for biogas and biomass, better power balancing, and acting as central power storage for prosumer-generated electricity. The main disadvantages are heavy infrastructure, a piping network both for heat and cold supply, distribution and metering problems among individual prosumers, and higher heat losses because the transfer of heat from the central plant to the district is already peaked.

Higher heat losses require more pipe insulation. In turn, high temperatures permit a higher temperature difference between the supply and return so that pumping power demand (lower fluid flow rates) may be reduced. For the cooling circuit, the same applies. The cold waste source must be closer to the district, which might require the placement of heat pumps somewhere between the plant and the district.

1.5. Quality or Quantity of Renewable Energy Sources

Any exergy mismatch among supply and demand points causes nearly-avoidable CO_2 emissions, which are as large as direct emissions in magnitude, and solar energy is not an exception. However, there have been few studies about solar energy and solar districts [12]. Science Europe Scientists also issued a memorandum on the critical need to consider the quality of energy, particularly in the built environment [13].

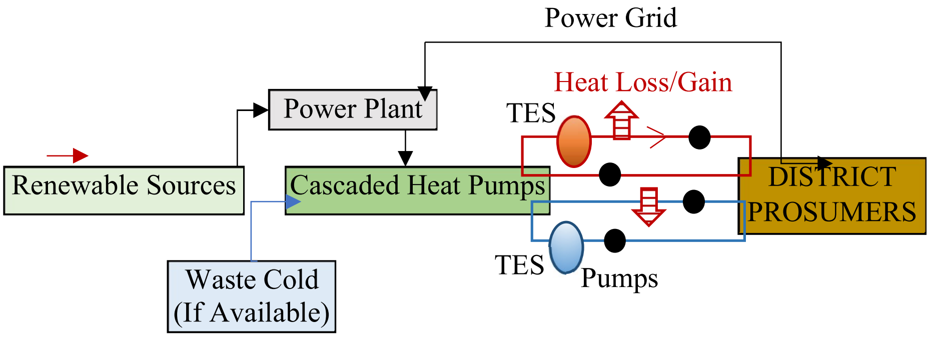

Fig. 1 Centralized Temperature Peaking in a District Energy System

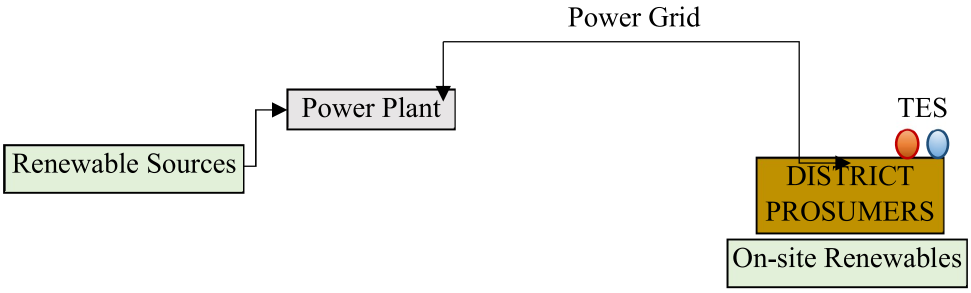

Fig. 2 De-centralized Temperature Peaking in a District Energy System

Solar Energy: The maximum quality of solar energy is derived by relating the solar constant, S_c outside the atmosphere (1.3661 kW/m^2), to the sun's surface temperature, 5778 K [14]. 0.95 kW/kW is the maximum unit electrical exergy that a PV cell may generate under such conditions if Q_{solar} is taken to be the solar insolation over 1 m^2 of PV area facing the sun at a global reference temperature of 283 K. Some Authors round it to a one kW/kW by definition. It is impossible because the reference temperature may not be 0 K. The source temperature may not be infinity.

$$\varepsilon_{solar} = \left(\frac{E_{Xsolar}}{Q_{solar}}\right) \le \frac{\text{(1-283 K/5778 K) kW/kW}}{\left(1.3661\ \text{kW/m}^2\times 1\text{m}^2\right)} = \frac{0.95\ \text{kW/kW}}{\left(1.3661\ \text{kW/m}^2\times 1\text{m}^2\right)} 0.695\ \text{kW/kW} \tag{3}$$

Therefore, the maximum *quality* of solar energy, $E_{Xsolar,}$ is 69.5% of the *quantity* of solar energy received, Q_{solar} in space. On earth, the unit solar exergy will be lower because the total solar insolation on a solar panel on earth, I_n, [kW/m^2], will be less than S_c:

$$\varepsilon_{solar} = \left(0.95\times I_n\right)/1.3661 \qquad \{I_n < S_c\} \tag{4}$$

For example, if I_n is 0.757 kW/m^2 and the solar insolation surface area, A_p, is 1 m^2, the maximum useful work potential that any solar panel, irrespective of its type, may supply on earth is given below. The actual amount depends on the solar system, i.e., flat-plate collector (FPC), photo-voltaic panel (PV), or photo-voltaic-thermal panel (PVT).

$$E_{Xsolar} \le 0.695\times Q_{solar} = 0.695\times I_n \times A_p = 0.695\times 0.757\ \text{kW/m}^2\times 1\ \text{m}^2 = 0.526\ \text{kW}\ .$$

Although none of the solar systems use fossil fuels, they are responsible for nearly avoidable (indirect) CO_2 emissions resulting from the quality of solar energy they reject upstream or downstream, the electrical or thermal power, or both they generate.

An FPC system shown in Fig.3-a supplies only thermal power and rejects the major portion of E_{Xsolar}, upstream instead of generating electrical power [15]. The loss of electric power generating opportunity needs to be offset somewhere, by some other technology, possibly by a mix of fossil fuels and renewables with a ratio of R_X. This additional fuel spending causes indirect CO_2 emissions responsibility in a district, which is now expressed in terms of the REMM efficiency, ψ_R.

$$CO_{2responsible} = c_K\left(1-\psi_R\right)\left(1-R_X\right) = c_K\left(1-E_{X\sup}/E_{Xsolar}\right)\left(1-R_X\right) \tag{5}$$

The factor (c_K) depends on the average direct CO_2 emissions of the energy sector, attributable either to electrical power generation and transmission over a typical grid (0.63 kg CO_2/kW-h, from fuel to plug) or on-site thermal power generation (0.27 kg CO_2/kW-h: natural-gas boiler). These values are based on the exergy of the lower-heating value of fossil fuels (Reference: natural gas with c = 0.2 kg CO_2/kW-h/0.87 [kW/kW]). In turn, the same FPC avoids direct CO_2 emissions from the grid in proportion to the thermal power it supplies. Table 1 gives sample data and the results in both quality and quantity.

$$CO_{2avoided} = c_K E_{X\sup}\left(1-R_X\right) \tag{6}$$

Therefore, for any solar energy system, the net CO_2 avoidance, ΔCO_2 will be the difference:

$$\Delta CO_2 = CO_{2avoided} - CO_{2responsible} \tag{7}$$

For a typical FPC (Fig.3-a), if R_X is 0.1 (10% renewables in the energy mix), T_1 is 340 K, and T_2 is 320 K (solar hot water supply and return temperatures, respectively, and η_{FPC} is 0.7, then per unit Q_{solar};

$$CO_{2responsible} = 0.63\left(1-\left(1-\frac{320\ \text{K}}{340\ \text{K}}\right)\times 0.7/0.695\right)\left(1-0.1\right) = 0.533\ \text{kg CO}_2\text{/kW-h}$$

$$CO_{2avoided} = 0.27\times\left(1-\frac{320\ \text{K}}{340\ \text{K}}\right)\times 0.7\times\left(1-0.1\right) = 0.010\ \text{kg CO}_2\text{/kW-h}$$

Table 1 shows the essence of considering the quality of energy in solar projects of any size and application. Table 1 also shows that energy quantity may sometimes mislead the designer or practitioner. For example, solar FPC has high energy quantity efficiency (0.70) but a very low output of solar quality (0.041 kW). Conversely, the PV panel has the lowest efficiency (0.18) but more than four times more solar quality output than FPC (0.171 W).

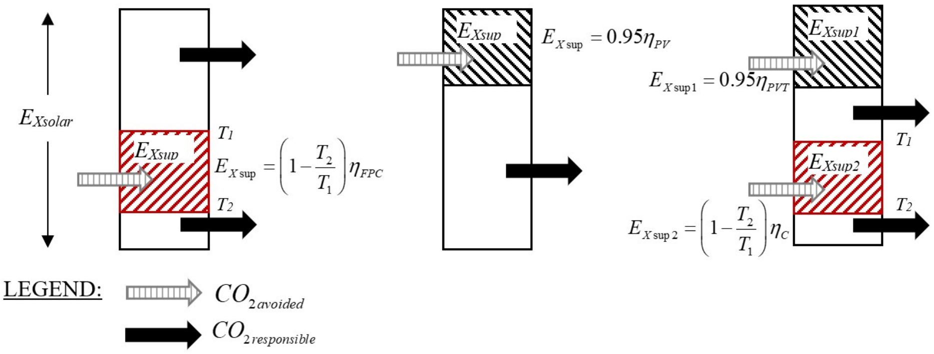

Fig. 3-a FPC Panel **Fig. 3-b** PV Panel **Fig. 3-c** PVT Panel

Table 1. E_{Xsolar} = 0.695 kW, R_X = 0.1

Solar System	Solar Energy Quantity, Q_{solar} = 1 kW				Solar Energy Quality, E_{Xsolar} = 0.695 kW					
	Power Generated	Energy Quantity Efficiency	T_1	T_2	E_{Xsup} [kW]		ψ_R	$CO_{2avoided}$	$CO_{2responsible}$	ΔCO_2
			[K]		Power	Heat		[kg CO₂/kW-h of solar energy]		
FPC	Thermal	η_{FPC} = 0.7	340 K	320 K	n/a	0.041	0.059	0.010	0.333	-0.433
PV	Electric	η_{PV} = 0.18	n/a	n/a	0.171	n/a	0.246	0.097	0.127	-0.030
PVT	Electric	η_{PV} = 0.20	n/a	n/a	0.190	n/a	0.324	0.108	~0	+0.108
	Thermal	η_c = 0.55	330 K	300 K	n/a	0.035		0.008	0.114	-0.034
	Totals for PVT				0.225			0.116	0.114	+0.006

$\Delta CO_2 = 0.010 - 0.533 = -0.433$ kg CO_2/kW-h (-ΔCO_2: positive carbon).

A PV cell generates electric power, upstream but misses the thermal power generation opportunity.
$\psi_R = E_{Xsup}/0.695 = (0.95 \text{ x } \eta_{PV} + 0.035 \text{ x } \eta_c)/ 0.695 = 0.246$
$CO_{2avoided} = 0.63 \text{ x } \eta_{PV} \text{ x } 0.95 \text{ x } (1-R_X) = 0.097$ kg CO_2/kW-h
$CO_{2responsible} = 0.27 \text{ x } (0.695-0.18 \text{ x } 0.95) \text{ x } (1-0.1) = 0.127$ kg CO_2/kW-h
$\Delta CO_2 = -0.030$ kg CO_2/kW-h (almost carbon neutral).

A PVT system combines both FPC and PV functions and thus minimizes quality rejections. A heat exchanging system cools the PV cells so that their power efficiency is maintained at high temperatures. $\psi_R = 0.225/ 0.695 = 0.246$.
$CO_{2avoided} = 0.63 \text{ x } \eta_{PVT} \text{ x } 0.95 \text{ x } (1-0.1) = 0.108$ kg CO_2/kW-h (With electrical power generated)

$$CO_{2avoided} = 0.27 \times \left(1 - \frac{300 \text{ K}}{330 \text{ K}}\right) \times \eta_c \times (1-0.1) = 0.012 \text{ kg } CO_2/\text{kW-h}$$ (With thermal power generated)

Total $CO_{2avoided} = 0.12$ kg CO_2/kW-h
$CO_{2responsible} = 0.27 \text{ x } 0.695 (1- \psi_R) \text{ x } (1-0.1) = 0.114$
$\Delta CO_2 = 0.12-0.114 = +0.006$ kg CO_2/kW-h (Carbon negative).

1.5. CO_2 Emission Responsibility of Not Utilizing Available Solar Insolation Areas

The above discussion may be extended further by questioning what happens if freely available areas for solar energy utilization are not used. If solar insolation surfaces are freely available, like building roofs, without much shading obstructions from the vicinity and do not have any other potentially more value-adding function options, this area is available for solar energy utilization. If not utilized, then this means that this surface has a CO_2 emissions responsibility, which is also an indicator for other greenhouse emissions. Three scenarios are identified:

- Photo-Voltaic (PV) System, Flat-Plate Collectors (FPC), Photo-Voltaic-Thermal (PVT) Panels

1.6.1. **SCENARIO 1**: PV Panel

This scenario corresponds to installing PV panels if feasible at a given location and expected demand (Only power). Until PV panels are installed, any unit area (A_p= 1 m^2) of available space for solar utilization will be responsible for direct emissions because no power is generated; thus, no CO_2 emissions are reduced from the stock. If PV panels are installed, electrical power will be generated upstream, and the corresponding amount of CO_2 emissions from the stock would be avoided in the power grid. However, the thermal power potential is lost downstream. This loss causes indirect (nearly-avoidable) emissions responsibility, namely ΔCO_2 (due to exergy loss) responsibility of installing PV panels (except embodiments). According to Fig. 4, the empty section represents the emissions responsibility of not installing PV panels. The dashed section is the ΔCO_2 responsibility that PV panels have because they only generate electrical power and destroy the rest of the solar exergy.

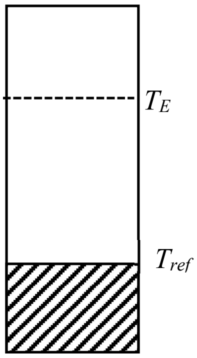

Fig. 4 Exergy Flow Bar for the Waste of Solar Area by PV Panel Installation

Then the net emissions responsibility of not installing PV panels will be the difference between grid emissions responsibility and the ΔCO_2 when installing PV panels.

$$\sum_{PV} CO_2 = \left[c \times PEF - 0.27\varepsilon_{des}\right] \times (1 - R_X) \tag{8}$$

$$\varepsilon_{des} = \left(1 - \frac{T_{ref}}{T_E}\right) \tag{9}$$

T_E is the PV panel temperature under design conditions without any cooling. T_{ref} is the reference environment temperature. For GSHP-based (ground-source heat pump) analyses provided in this chapter, a stable reference temperature has been selected to an average ground temperature of 283 K.

1.6.2. SCENARIO 2: FPC Panel

If only FPC panel installation is feasible at a given location and expected demand (only Heat). According to Fig. 5, the empty section represents the emissions responsibility of not installing FPC panels, and the dashed section is the ΔCO_2 responsibility if FPC panels are installed just for hot water supply. The rest of the solar exergy is destroyed in the FPC system.

$$\sum_{FPC} CO_2 = \left(\frac{c}{\eta_B}\right) - 0.63\varepsilon_{des} \tag{10}$$

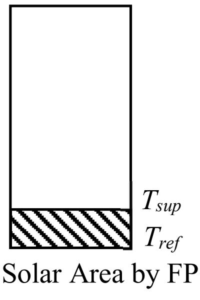

Fig. 5 Exergy Flow Bar Showing the Waste of Solar Area by FPC Panel Installation

$$\varepsilon_{des} = 0.95 - \left(1 - \frac{T_{ref}}{T_{\sup}}\right) \quad (11)$$

Usually, the net balance is negative. FPC systems have higher ΔCO_2 responsibility, and economic and environmental footprints exceed potential benefits.

1.6.3. CASE 3: PVT Panel

If PVT panel installation is feasible (Climate, demand profiles, temperature peaking requirements, etc.) at a given location and expected function (Power and Heat Generation)

According to Fig. 6, empty sections representing the ΔCO_2 responsibility are limited because electrical and thermal powers are generated at the same unit panel area.

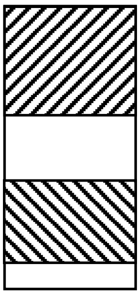

Fig. 6 Exergy Flow Bar Showing the Waste of Solar Area by PVT Panel Installation

$$\sum_{PVT} CO_2 = \sum_{PV} CO_2 + \sum_{FPC} CO_2 \quad (12)$$

A_p is the same (1 m^2) because a PVT system overlays PV and FPC on almost a single area. These equations show that a building owner is responsible for not utilizing the free solar area (except for heat island effects, and shading effects), if not useful for other purposes, and if the PVT system is feasible. Therefore, FPC systems are not useful at all. For example, roof areas must be allocated to more useful applications like green roofs.

References

[1] Blum, P., Campillo, G., Munch, W., and Kölbel, T. 2010. CO_2 Savings of Ground Source Heat Pump Systems - A Regional Analysis, Renewable Energy 35 (2010), pp: 122-127.

[2] Kılkış, Ş. 2014. Energy System Analysis of a Pilot Net-Zero Exergy District, Energy Conversion and Management 87 (2014), pp: 1077-1092. <http://dx.doi.org/10.1016/j.enconman.2014.05.014>

[3] Kilkis, S. 2012. Green Cities and Compound Metrics Using Exergy Analysis. *In* Encyclopedia of Energy Engineering and Technology. Taylor and Francis: New York, Published online: 23 Jul 2012; 1-7. <http://dx.doi.org/10.1081/E-EEE-120047398>

[4] EC. 2014. Most Residential Buildings Were Built Before Thermal Standards Were Introduced, How Do you Know? Energy, Chart: Breakdown of Residential Building by Construction Year. <https://ec.europa.eu/energy/content/most-residential-buildings-were-built-thermal-standards-were-introduced_en>

[5] Dijk, HAL van, Bruchem, L van and Wolveren, J van. 1998. Voorstudie naar de effecten en het gedrag van Laag Temperatuur Systemen, Delft, 1998.

[6] Hesaraki, A., Ploskic, A., and Holmberg, S. 2015. Integrating Low-temperature Heating Systems into Energy Efficient Buildings, Energy Procedia, Volume 78, November 2015, pp: 3043-3048.

[7] IEA. 2000. EBC Annex 37, LowEx, Literature Review: Side Effects of Low Exergy Emission Systems, 100 pages, Novem BV. the Netherlands.
https://annex53.iea-ebc.org/Data/publications/EBC_Annex_37_literature_review.pdf

[8] Eijdems, H. H. E. W., Boerstra, A. C., and Opt `t Veld`, P. J. M. 2000. Low-Temperature Heating Systems Impact on IAQ, Thermal Comfort, And Energy Consumption, Healthy Buildings Conference, August 2000, <https://www.healthyheating.com/IEQ_Radiant.htm>

[9] Kılkış, B., Kılkış, Ş. 2018. Rational Exergy Management Model for Effective Utilization of Low-Enthalpy Geothermal Energy Resources. Hittite Journal of Science and Engineering, 5 (0), 59-73. DOI: 10.17350/HJSE19030000119

[10] Jansen, S., and Woudstra, N. 2010. Understanding the Exergy of Cold: Theory and Practical Examples, *Int. J. Exergy*, Vol. 7, No. 6, pp.693–713.

[11] Kilkis, B. 2021. Is Exergy Destruction Minimization the Same Thing as Energy Efficiency Maximization? *Journal of Energy Systems*, 2021; v(i), DOI: 10.30521/jes.

[12] EBC. 2018. EBC ANNEX 64 LowEx Communities-Optimised Performance of Energy Supply Systems with Exergy Principles, Completed in 2018, Fraunhofer Institute for Wind Energy and Energy System Technology Kassel, <https://iea-ebc.org/projects/project?AnnexID=64>

[13] SE, Science Europe. 2016. In a Resource-Constrained World: Think Exergy, not Energy, PublishedJune 2016. Science Europe, Brussels. <https://www.scienceeurope.org/media/0vxhcyhu/se_exergy_brochure.pdf>

[14] Kilkis, B. 2020. Accelerating the Transition to 100% Renewable Era. But How? Exergy Rationality in the Built Environment. In: Uyar, TS, Editor, Accelerating the Transition to a 100% Renewable Energy era. Cham, Switzerland: Springer International Publishing, 2020. pp:1-49. doi.org/10.1007/978-3-030-40738-4

[15] Kilkis, B. 2021. The Relationship Between Climate Emergency, Pandemics, and Buildings- COVID-19 Has a Vaccine Now but Climate Emergency Has not, *BRIQ J.*, Vol. 2, Issue: 3. pp: 61-68.

[16] Birol Kılkış, B., Çağlar, M., and Şengül, M. 2021. The Exergetic Benefits of Heat Pipe Technology for Achieving 100% Renewable Heating and Cooling for Fifth-Generation, Low-Temperature District Heating Systems, Energies Journal: *Energies* 2021, *14*, MDPI.

[17] Koroneos, C. and Kalemakis, I. 2012. Exergy indicator in the Built Environment, *Int. J. Exergy,* Vol. 11, No. 4.

[18] Kılkış, B. 2019. The Importance of Exergy Rationality and Storage for 100% Renewable Targets in Decoupling Sustainable Development and Ozone Depletion, UNIDO Workshop on Ozone, September 16-17 2019, Antalya.

[19] ETB. 2021. The Engineering Toolbox, Refrigerants-Environmental Properties, Refrigerants - Ozone Depletion (*ODP*) and Global Warming Potential (*GWP*). <https://www.engineeringtoolbox.com/Refrigerants-Environment-Properties-d_1220.html>

[20] Kilkis, I. B. 2000. Rationalization and Optimization of Heating Systems Coupled to Ground Source Heat Pumps, *ASHRAE Transactions,* Vol. 106, Pt. 2, pp. 817-822, 2000. *ASHRAE Transactions*, MN-00-13-1.

[21] Kilkis, B. 2021. An Exergy-Based Minimum Carbon Footprint Model for Optimum Equipment Oversizing and Temperature Peaking in Low-Temperature District Heating Systems, *Energy Journal*, Paper No: EGY_121339.

[22] ASHRAE. 2020. Chapter 6, *ASHRAE HB, HVAC Systems and Equipment*, ASHRAE: Atlanta

[23] Kılkış, B. and Taseli, B. K. 2021.Two-Step Onboard Hydrogen Generation from Black Sea H_2S Reserves, *Int J Energy Res.* 2021, 45:7177–7192. DOI: 10.1002/er.6304

[24] Uyar, T. S. (Ed.). 2019. Lecture Notes in Energy, Vol. 74, ISBN 978-3-030-40737-7 ISBN 978-3-030-40738-4 (eBook) <https://doi.org/10.1007/978-3-030-40738-4>

[25] RHC-ETIP. 2019. Position Paper on Horizon Europe Work Program, Posted on July 22, 2019 <https://www.rhc-platform.org/rhc-etip-position-paper-on-horizon-europe-work-programme/>

[26] Gawer, R., and Cezarz, N. 2016. Stanford University: Economic, Efficient, Green District Low Temperature Hot Water, IDEA Annual Conference, Detroit, Mich., USA, 2016.

[27] SDH, 2018. Sun Meets 90 % of District Heat Demand in Tibet, Solar District Heating, EU. <https://www.solar-district-heating.eu/sun-meets-90-of-district-heat-demand-in-tibet/>

[28] Kilkis, B. 2020. Exergy-Based Hydrogen Economy With 100% On-Board Renewables, H_2S Reserves, and Coastal Hydrogen Cities in the Black Sea Region, Special Report to Turkish Ministry of Energy and Resources (MENR), 79 Pages, August 30, 2020, Ankara, Turkey.

[29] OU. 2021. Chapter 9: Carbon Dioxide (R744) - The New Refrigerant