AN EXERGY-RATIONAL DISTRICT ENERGY MODEL FOR 100% RENEWABLE CITIES WITH DISTANCE LIMITATIONS

by

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While moving towards 100% renewable district energy systems at low temperatures, the exergy of the district energy may decrease below the pumping exergy requirement, which eliminates the benefits of using low-exergy renewables. Because such a possibility may not be revealed by the First Law, an exergy-based holistic model for district energy systems was developed. Four tiers, namely renewable energy resources, energy conversion and storage, main district network, and the low-exergy district are identified. Each tier is indexed to the optimum plant-to-district distance for maximum exergy-based performance with minimum CO_2 emissions responsibility. This model further optimizes the temperature peaking with heat pumps versus HVAC equipment oversizing and determines the optimum mix of renewables. Three alternatives of conveying and distributing exergy to the district were considered, namely: electricity only, electricity and heat with or without temperature peaking or equipment oversizing, and electricity, heat, and cold. Comparisons showed that the choice primarily depends upon the district size, district-to-plant distance, climatic conditions, local availability of RES, optimum supply temperature, and thermal condition of the buildings. Another algorithm optimizes the thermal insulation thickness in terms of equipment oversizing and temperature-peaking.

Keywords: *exergy, low-exergy district energy system, low-exergy building, maximum piping distance, equipment oversizing, temperature peaking*

Introduction

This paper hypothesizes that an environmentally admissible district energy system is possible only if it designed and operated according to the Second Law of thermodynamics and paves the way for the accomplishment of the 2030 EU climate and energy framework. This framework includes binding targets and policy objectives of reducing GHG emissions by at least 40% from 1990 levels, to increase the share of renewables by at least 32% of final energy consumption, and to improve energy efficiency by at least 32.5% [1]. Among these targets, low temperature district energy systems are becoming a focal point for potential solutions. This paper is expected to contribute by expanding this concept into a dynamic design and control tool for maximum exergy rationality for nearly-zero emissions. For increasing the share of renewables for 100% renewable cities (100REC), it is necessary to tap in widely abundant but unexploited low-exergy renewables. Figure 1 shows the historical trend with

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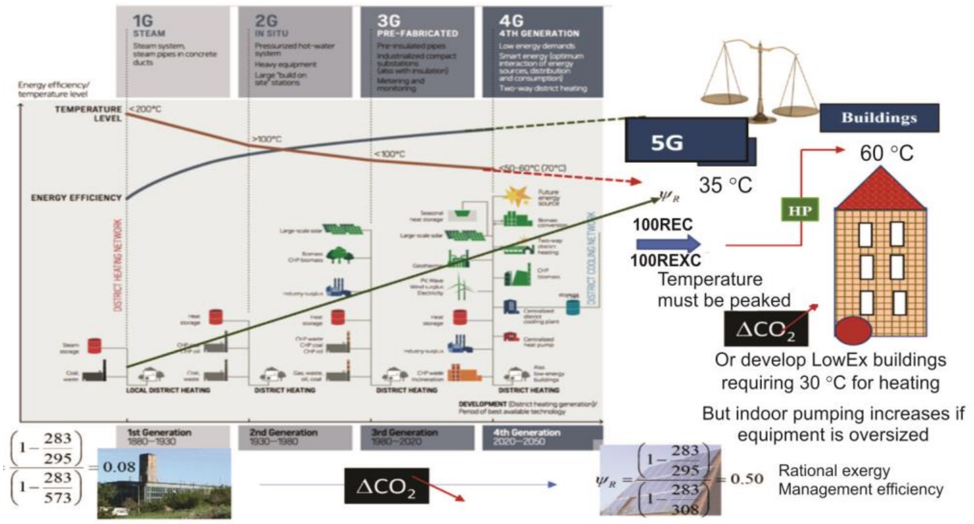
steam heating with >200 °C, named 1G (first-generation) leading to poor energy (First law) efficiency, η_{I}, and exergy rationality, ψ_{R} (Second Law). The system got better and diverse in terms of renewables with lower supply temperatures for higher efficiency, better exergy rationality, and temperatures decreased below 60 °C, which is named 4G [2-4].



Note: The Original Figure Expanded, Extrapolated, and Modified from [2, 3, 4]

Figure 1. Historical evolution of district energy systems and the handicap with existing building stock

Today, district heating systems with 35 °C supply temperatures are considered (5G), potentially leading to 5G^{+} systems, which shall involve even lower supply temperatures. For example, the EU project RELaTED in Denmark involves an ultra-low temperature district heating demonstration project at a temperature range of 45-30 °C [5]. Dealing with low-exergy sources, the essence of exergy balance between supply and demand became more recognizable such that equipment oversizing and/or temperature peaking in buildings renders the advantages pointless in terms of economy, environment, energy, and exergy. For example, an electrically driven heat pump seems to be energy efficient. Yet the large difference between unit exergy of electricity (0.95 W/W) and the low temperature heat (below 0.10 kW/kW) requires a COP of 9 or above to be exergy-even. Otherwise, destroyed exergy leads to avoidable CO_2 emissions, ΔCO_2. At low supply temperatures, the difference between the supply and return temperatures both in the building and the district network must also be small. This leads to high power demand by pumps and fans unless the pipe and duct diameters are selected larger, which in turn will be responsible for additional embodiments of cost, CO_2, exergy, energy, and material. Temperature-peaking generates more GHG and ozone-depleting emissions, compounded by additional material, energy, CO, and exergy embodiments and more pump power for fluid circulation in the oversized equipment. Two definitions follow [4, 6]:

- The 100REC is a city with defined municipal/administrative boundaries, which on an annual basis, satisfies at least 75% of its power, heat, and cold demand from renewables in its boundaries, with proper thermal and electrical energy storage mediums and if the remaining 25% is imported from external renewables.
- The 100REXC is a city with defined municipal/administrative boundaries, which on an annual basis satisfies at least 75% of the total power, heat, and cold exergy demands from

renewables, with sufficient thermal and electrical energy storage mediums and if the remaining 25% is satisfied by outside renewables and the annually-averaged city-wide rational exergy management efficiency, ψ_R is not less than 0.50.

Energy watch group [7] outlined a 1.5 °C scenario for global warming emergency with a cost-effective, cross-sectoral, technology-rich global 100% renewable energy system. Their model simulates a total global energy transition in the electricity, heat, transport, and desalination sectors by 2050 to prove that the transition to 100% renewable energy is economically competitive with fossil and nuclear-based systems leading to zero emissions even before 2050. Another technical barrier to 5G systems is the increased sensitivity of exergy destructions by lower supply temperatures, which is shown in fig. 2. This makes the precise control of heat supply in response to dynamically changing loads more difficult. When this difficulty is coupled with the fact that the difference between the supply and return temperatures, ΔT, decrease, there is also a need for more accurate and sensitive heat measuring devices like thermal pulse meters. The minimization of exergy destructions requires a good exergy balance between the low-exergy district and low-exergy buildings [8]. In this respect, the district of Ostra Sala Backe in Uppsala Municipality in Sweden planned a near-zero energy district for 20000 residents, including combined heat and power, heat pumps, which are driven on renewable energy, smart home automation, efficient lighting, and bioelectricity-driven public transport. The annual exergy that is produced in the district is optimized by REMM, through eight measures, supplying thermal exergy of 49.7 GWh, where the annual exergy consumed is 54.3 GWh. This corresponds to an exergy match with 84% [8]. On the other hand, through its various projects and publications, the IEA EBC Annex 64-LowEx Communities demonstrates the potentials of low exergy thinking on a community level as energy and cost-efficient solutions towards 100% renewable and GHG-free systems. Central challenges are the identification of promising and efficient technical solutions for practical implementation [9].

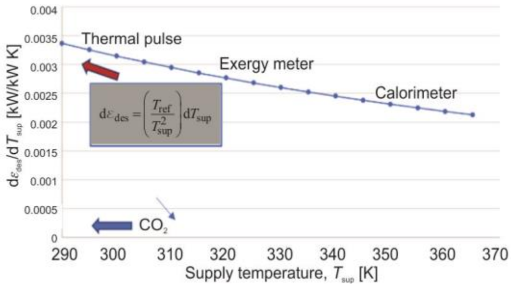


Figure 2. Variation of destroyed exergy with supply temperature [4]

In line with 100% renewable heating and cooling for a sustainable, low-exergy future, EU RHC is emphasizing on district energy systems for better and concerted utilization of renewables, establishing an important strategic part of the decarbonization and electrification efforts [10], while four key cross-cutting technology areas were identified. The first one is the district heating and cooling. Other key areas are thermal energy storage, heat pumps, and hybrid renewable energy systems, combining two or more energy sources into a single system to overcome the limitations of individual technologies. According to Gong and Werner [11], another consequence of the current level of distribution temperatures if fossil fuels are used is that two-thirds of the exergy content fed into the hydronic distribution networks are lost in the heat distribution chain before fulfilling the final customer temperature demands. In this case implementation of LowEx buildings does not make much sense due to large unit exergy difference between the fossil fuel and unit exergy of the building. This is one of the reasons for 100% renewable cities. On the other hand, they gave the first clues about the importance of exergy rationale especially when low-exergy renewables used by mapping energy and exergy flows in Sweden. Harvey claimed that it will be necessary to replace fossil fuels in any case with hydrogen fuel in applications where renewable energy resources may not be directly utilized [12]. The pioneering work on solar-assisted district heating was carried out in Sweden during the 1970's and 1980's. By 2003, eight solar-assisted district heating systems had been constructed under the German Solarthermie-2000 program. Fischedick *et al.* [13] provided a wide review of an all-renewable energy system using hydrogen and electricity as interchangeable energy assets. A hydrogen economy district energy system was introduced recently [14] and Dincer and Rosen [15] gave a detailed analysis of hydrogen production from solar and wind systems with their embodied exergy consumption. District cooling is also possible by low-exergy cold sources like a deep lake and seawater [13]. For example, in an urban renewal project in the Italian seaport of Livorno covering 63 apartments and 37 shops rely on seawater for district cooling through two heat pump stations [16]. The authors claimed an average COP value of 4.09 in heating mode supplying hot water at 48.9 °C (322K). What misses in this article is the exergy rationality, such that at the given supply temperature and for a reference temperature of 283 K, the exergy-based COP reduces to 0.495 according to the ideal Carnot cycle. Lund [17] has introduced the concept of smart energy systems approach via the EU EnergyPLAN code (Advanced Energy System Analysis Computer Model) for 100% renewables. A smart thermal grid is a parallel term to the smart electricity grid, in such a manner that it responds to fluctuating renewable energy resources by proper controls and allocation schemes. In this code, the objective is maximum efficiency (First law) and affordable cost. However, the exergy constraints (Second law) on the objective function are not included. In the same token, the very first district energy company that coined the term Exergy in their CHP-based district energy system title is in Stockholm, Sweden [18]. The so-called Stockholm Exergi's goal is to utilize 100% renewable fuels by 2022, which is in line with the aim of the city of Stockholm to be a fossil-fuel-free city by 2040. The Brandenburg town of Hennigsdorf planned to increase the climate-neutral share of heat in its existing district heating network to 80% in five years, by integrating the waste heat at a maximum temperature of 60 °C (333K) from local steelworks and 854 m^2 solar thermal collectors. A large thermal storage system provides sufficient flexibility. By 2020 it is expected to have 81% CO_2 neutrality with the contribution of bio-natural gas, forest wood, solar thermal, waste heat, and fossil fuels [19]. The distance between the plant and the district, especially in low-exergy renewable energy district heating and cooling is very important. But the few available works of literature on this topic depend on the First law and economy only. For example, Prando *et al.* [20] have developed a numerical model for the thermal behavior of a district heating network and calculated its performance in terms of cost-optimal building refurbishment, focusing on 13 micro-networks located in South Tyrol, Italy, and investigated the optimum building refurbishment for constant heat price and provided data about a relationship between the thermal load decrease and the distribution cost for fixed piping design. Although it covers a limited number of buildings, it shows the dependence of the piping length and thermal loads as a function of the number of buildings that may have a closely-linear relationship, which is shown in fig. 3. Arguing that current designs depend on recommended values for specific pressure loss ($R = \Delta P/L$) about economically feasible solutions, Wang *et al.* [21] developed an optimization model by considering the initial investment of piping and pumping costs. The resulting CO_2 emissions responsibility both during operation (pumps, *etc.*) and due to material embodiment and exergy difference between electricity, heat, and cold were not considered. Kavvaidas and Quoilin [22] investigated the maximum distance permitted to transport low-grade waste heat from industrial processes or thermal power plants for long distances, simply by using the First law of Thermodynamics and developed a techno-economic model. Their study involved the supply temperature in addition to the work reported in reference [21]. They introduced an approximate equation, for $L_{\max}$ as a function of the square-root of the thermal power, $\dot{Q}_D$ [MW], multiplied by a constant, which depends on the supply temperature, thermal energy price, electricity price, and $\dot{Q}_D$. Ljubenko *et al*. [23] referred to exergy by noting that lowering the exergy more renewable and low-quality waste heat sources may be exploited.

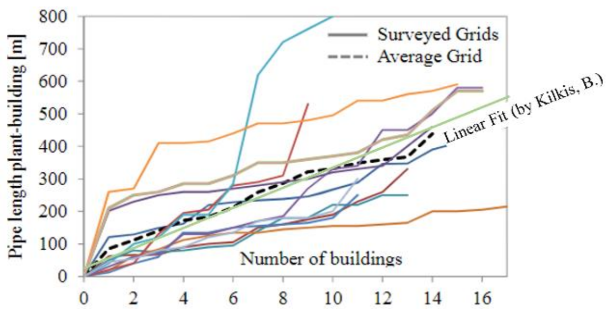


Figure 3. Plant to buildings distance; reproduced from [20] with an added linear fit

They developed an exergy-based distribution-network analysis model and introduced new criteria for performance. Their model is based on the primary pipeline between the supply and demand points in the district heating system and a case study about the district heating of Saleska Valley revealed a relationship among optimal supply temperature, pipe diameters, and district capacity *vs*. exergetic efficiency and have shown that with such an optimization and sensitivity analysis, a conventional design may be substantially improved. Verda *et al*. [24] made another thermo-economic analysis of a district heating system, which shows that the average exergo-economic unit cost of the district supply mainly depends on the exergy flow and mechanical power required. Sangi and Muller [25] applied the Second law to control, which also applies to district energy systems in general. They stated that for proper performance and environmental benefits, exergy-based control is necessary because district energy systems are highly dynamic. A simple relationship states that $L_{\max}$ is proportional to $\dot{Q}_D$, sometimes numerically raised to a power constant [8, 26-28].

Aim of the research work

This research aims an exergy-based holistic model, which will be instrumental in optimizing the design and operation of successful 5G districts for improving the overall COP_{EX} value by primarily focusing on the plant-to-district distance. All studies in the literature analyze the plant-to-district distance in a simple format, which is isolated from the resources, the district plant, and the buildings on the demand side. These studies were also carried in terms of the First law, without taking the embodiments into account. None of them holistically covered the four tiers of this research.

Preliminary model

Start-up model

There is a simple connection between the district plant and the district, fig. 4. The electrical power demand of the circulation pump station(s) and the exergy of supply and demand sides are noted. There is a temperature-peaking heat pump, which comes with a penalty of ozone-depleting potential (ODP) and global warming potential (GWP) due to its indirect CO_2 responsibilities, and refrigerant leaks. The ODP and GWP are closely related, which was recently expressed by a composite, ODI [29]. According to preliminary studies, the constants are: $w = 0.1$, $y = 0.045$, and $z = 0.01$, where y includes the water vapor released from cooling towers, which has a greenhouse effect leading to GWP:

$$ODI = \frac{wGWP^{y}}{(1-ODP)}\left(\frac{ALT}{1}\right)^{z} \qquad \{ODP, <1\} \tag{1}$$

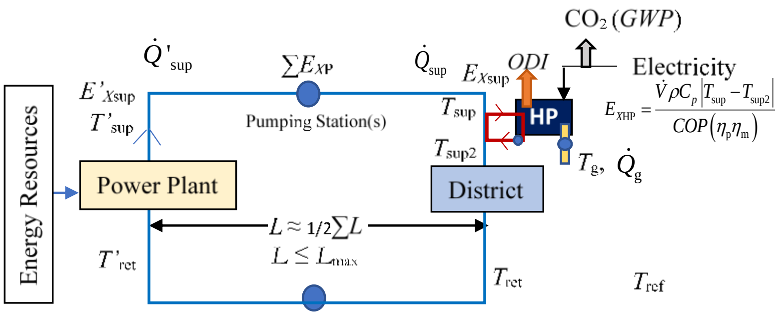


Figure 4. Start-up model for district energy system with a distant power plant

Recognition of the handicaps of low exergy district energy systems

By acknowledging that only low-exergy demand exists in a low-exergy district and there are low exergy renewable energy resources available, but pumping demand remains to be high-exergy, the exergy balance is getting more important than the thermal load balance. For a given district thermal power demand, $\dot{Q}_{\mathrm{sup}}$, and a given reference environment temperature, T_{ref}, thermal supply power exergy, and pumping exergy are not considered:

$$E_{X\,\mathrm{sup}} = \dot{Q}_{\mathrm{sup}}\left(1-\frac{T_{\mathrm{ret}}}{T_{\mathrm{sup}}}\right) \qquad \{\text{In district heating}, T_{\mathrm{sup}} > T_{\mathrm{ret}}\} \tag{2}$$

$$E_{X\,\mathrm{sup}} = \dot{Q}_{\mathrm{sup}}\left(1-\frac{T_{\mathrm{ret}}}{T_{\mathrm{sup}}}\right) \qquad \{\text{In district cooling}, T_{\mathrm{sup}} < T_{\mathrm{ret}}\} \tag{3}$$

$$\sum E_{XP} = C\dot{Q}_{\mathrm{sup}}^{3}\sum L \times (0.95\ \mathrm{kW/1\ kW}) \simeq C\dot{Q}_{\mathrm{sup}}^{3}\sum L \quad \{\text{From Affinity law}\} \tag{4}$$

For a positive exergy gain, either eq. (2) or eq. (3) must be greater than eq. (4), which expresses the total exergy demand of the pumping power needed in the district network. Otherwise, the system will not be exergy-rational because more exergy will be spent than the exergy delivered to the district. In eq. (4), ΣE_{XP} is the total electrical power demand of the district pump station(s) with unit exergy of 0.95 kW/kW, (Approximately 1). In fig. 4 plant and city variables are differentiated with (‘) to take into account the thermal losses (gains) and fluid temperatures in the piping.

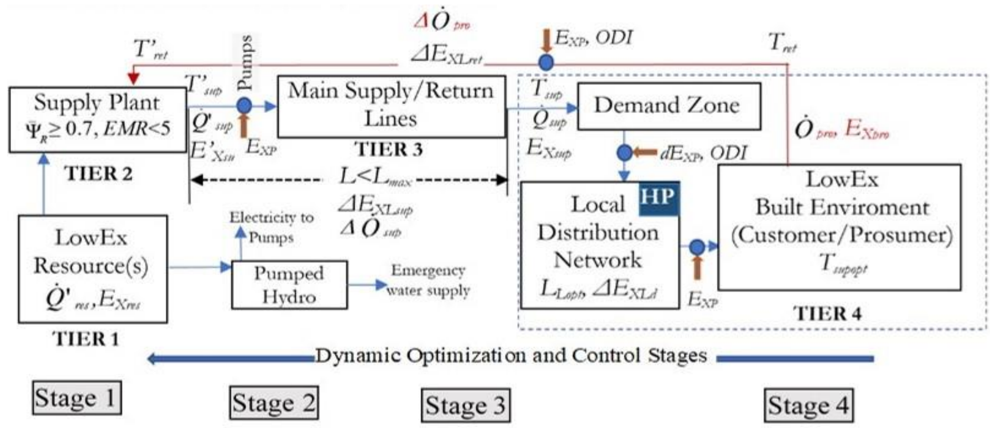
Possible remedies for the Low-exergy district handicap

Case 1: The HVAC equipment oversizing (without temperature peaking)

The exergy balance between supply and pumping determines the minimum T_{sup} and thus T'_{sup} by simultaneously solving eqs. (2) or (3) and (4), for a given ΔT between district supply and return, with the $NetE_{X\mathrm{sup}} = 0$ condition. Due to difficulties in exergy metering and helping to maintain the rated performance of the equipment is ΔT kept quite low, as low as 5 K even lower:

$$NetE_{X\,\text{sup}} = E_{X\,\text{sup}} - \sum E_{XP} \tag{5}$$

$$T_{\text{sup}} \geq \frac{\Delta T}{C\dot{Q}^2 \sum L} \quad \{\text{Without temperature peaking}\} \tag{6}$$



Note: (`) means the plant side

Figure 5. Four tiers of the holistic district energy model

If the equipment performance is compromised while the district network is optimized for lower T_{sup} values then an optimum mix of temperature peaking and equipment oversizing factor (OF) is necessary for the maximum use of low-exergy renewables towards 5G districts. Retrofits such as oversizing radiators may not be easy if indoor spaces are restrictive while plumbing also needs to be proportionately oversized for minimum impact on pumping exergy demand, P_{SR}. The OF is given by eq. (7) [30]:

$$OF = \frac{c\left(T_{\text{f,design}} - T_{\text{a}}\right)^n}{c\left(T_{\text{f,5G}} - T_{\text{a}}\right)^n} \simeq \left[\frac{T_{\text{f,design}} - T_{\text{a}}}{T_{\text{f,5G}} - T_{\text{a}}}\right]^n \quad \{OF \geq 1\} \tag{7}$$

$$P_{SR} = \left\{ \frac{\left(T_{\text{sup,design}} - \dfrac{\Delta T_{\text{design}}}{2} - T_{\text{a}}\right)}{\left(T_{\text{sup,f,5G}} - \dfrac{\Delta T_{\text{sup,5G}}}{2} - T_{\text{a}}\right)} \right\}^{3n} \tag{8}$$

Utilization of the lowest-exergy resources with low ΔT in the hydronic circuit, without compromising the COP of heat pumps at the minimum need for temperature peaking is possible only by LowEx buildings, which also reduce the embodied energy, exergy, cost, and CO_2 emissions attributable to their power demand, $E_{X\text{HP}}$, and minimize refrigerant leakages.The $E_{X\text{HP}}$ depends on the COP [4]:

$$COP = q - r\left|T_{\text{sup}2} - T_{\text{sup}}\right| \tag{9}$$

If the district heat is going to be utilized also in an open system, like domestic hot water supply, then T_{sup} or T_{sup2} needs to satisfy the limits set for minimizing Legionella risk. This may require another set of temperature peaking limit. When all these parameters are considered, it becomes clear that the city (Tier-4, fig. 8) needs special care and exergy-oriented optimization. In conclusion, the distance between the central plant and the district network becomes more critical when low-exergy heat or cold is circulated. For example, if instead of 90-70 °C supply and return temperature with unit exergy of 0.055 W/W, 40 °C to 30 °C is in place, only 0.032 W/W is circulated. The latter becomes less comparable with the power exergy demand of the pump stations, rendering exergy a dominant parameter in determining the maximum allowable distance [31-34].

Case 2: Temperature peaking with heat pump (without HVAC equipment oversizing)

The term $\Sigma E'_{\mathrm{XP}}$ includes the power demand of additional circulation pumps and the ground loop, where $\dot{V}$ is the volume flow rate of the circulating fluid in the district loop with the given average thermophysical properties ρ and C_p. The η_{p} and η_{m} are respectively the pump drive, and the motor efficiencies:

$$NetE_{X\,\mathrm{sup}} = E_{X\,\mathrm{sup}} - \sum E'_{\mathrm{XP}} - E_{X\ \mathrm{HP}} \tag{10}$$

$$T_{\mathrm{sup}} \geq \frac{T_{\mathrm{ref}}}{\left(1 - C\dot{Q}_D^2 \sum L - \dfrac{\dot{V}\rho C_p \left|T_{\mathrm{sup}} - T_{\mathrm{sup2}}\right|}{COP\left(\eta_{\mathrm{p}}\eta_{\mathrm{m}}\right)}\right)} \quad \{\text{With temperature peaking}\} \tag{11}$$

Case 3: The optimum mix of temperature peaking and equipment oversizing

The objective is to pair low-temperature renewables with low-temperature districts with little or no need for temperature peaking to satisfy the recent 5G$^+$ trend.

STEP 1 – Economic optimization

Equation (12) determines the $T_{\mathrm{f,opt}}$ (point C in fig. 6) for minimum life-cycle cost regarding heat pump *vs.* equipment oversizing. Here, C_{eq} and C_{hp} are the life-cycle cost factors [€/Wh] for the equipment and the heat pump at their rated operating temperatures, respectively. If the supply temperature T_{sup} needs to be peaked ($T_{\mathrm{sup}} < T_{\mathrm{f,HP}} < T_{\mathrm{f,eq}} < T_{\mathrm{sup2}}$), temperature deficits namely $C_2 = (T_{\mathrm{f,eq}} - T_{\mathrm{a}})$ and $C_1 = (T_{\mathrm{f,p}} - T_{\mathrm{g}})$, respectively need to be compensated to maintain the original thermal performance by partially oversizing the heat pump ($\mathrm{OF_{HP}}$) and the equipment($\mathrm{OF_{eq}}$) by using eq. (12). The $T_{\mathrm{f,opt}}$ is the optimum operating temperature, $T_{\mathrm{f,eq}}$ and $T_{\mathrm{f,HP}}$ are the rated operating temperatures of the equipment at an indoor temperature T_{a}, and the heat pump ground heat at a temperature T_{g}, respectively:

$$T_{\mathrm{f,opt}} = \sqrt{\frac{\dfrac{C_{\mathrm{eq}}C_2}{C_{\mathrm{HP}}}}{C_1}} + T_{\mathrm{a}} \tag{12}$$

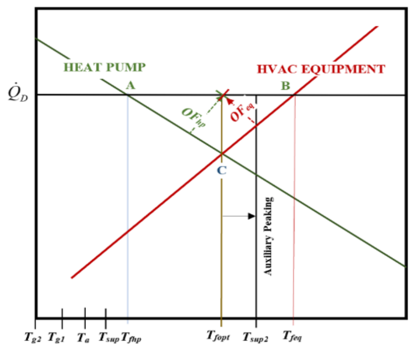


Figure 6. The linearized performance conflict between heat pump and HVAC equipment [35]

STEP 2 – Tandem Heat Pumps

Figure 7 shows one large temperature lift-heat pump and a multitude of tandem heat pumps with smaller temperature lifts. In this strategy, ΔT_{i} is kept constant along the temperature peaking path for each heat pump (i). According to previous studies, only two heat pumps in tandem gives the best result [36]:

$$\Delta T_o = T_{sup2} - T_{sup} \tag{13}$$

$$\Delta T_i = \left(\frac{\Delta T_o}{N_{HP}}\right) = \text{constant} \tag{14}$$

$$COP_i = q - (r\Delta T_i) = q - r\left(\frac{\Delta T_o}{N_{HP}}\right) \quad \{N_{HP} = 2\} \tag{15}$$

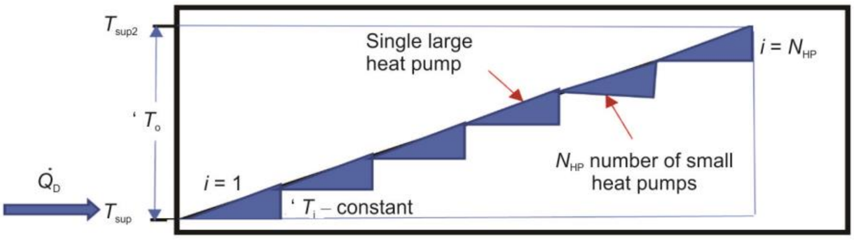


Figure 7. Temperature peaking with a multitude of *N* number of smaller heat pumps in tandem

The need for an exergy-based model

Low-Exergy, "High-Efficiency" renewable/waste energy systems and equipment which are not generally collocated, often fail in terms of the Second law of thermodynamics at the absence of an exergy-based model. Consider a ground-source heat pump that delivers hot water to a building at a T_{sup2} temperature of 55 °C (328 K). The ground-source temperature T_g is 283 K. If the electric power input to the heat pump is 1 kW, then the thermal power delivered will be COP kW, assuming that the ambient exergy input and parasitic exergy destructions (pumps, *etc*.) are ignored. The corresponding exergy of the thermal power delivered to the building according to the ideal Carnot cycle is *COP* × (1-283 K/328 K), which is only (0.137 × *COP*) kW. Therefore, the minimum COP must be 7.3 (1 kW/0.137 kW) for the exergy break-even condition. A COP_{EX} term for a simple heat pump case was defined. For example, from eqs. (9) and (16), the optimum supply temperature, $T_{sup2,opt}$ for maximum COP_{EX}, which represents the optimally maximum exergy gain may be determined. The COP_{EX} and the unit exergy destruction, ε_{des} are inversely proportional and, ε_{des} is related to the avoidable CO_2 emissions, ΔCO_2 by referencing it to a natural-gas non-condensing boiler, 0.87 kW/kW of unit exergy, 0.2 kg CO_2/kWh, thermal efficiency 85% in eqs. (19) to (23). Such derivations are not possible by the COP definition given in eq. (9), which only shows that T_{sup2} should be close to T_g. Therefore the First law must always be accompanied by the Second law for environmentally responsible designs. A simple heat pump is a piece of stand-alone equipment with one energy source input port and one energy supply port:

$$COP_{EX} = COP\left(1 - \frac{T_g}{T_{sup2}}\right) \quad \{\text{Simple heat pump only}\} \tag{16}$$

$$T_{sup2max} = \sqrt{T_g\left(\frac{q}{r}\right) + rT_g} \quad \{\text{For maximum } COP_{EX}\} \tag{17}$$

Development of the holistic discrict energy model

New rules of exergy and emissions

In pursuing the aim of this work, the following rules were compiled. For a sustainable and exergy-rational district energy system the minimum REMM efficiency, ψ_R is set by the following green district condition [4, 33]:

$$\psi_{Ri} \geq 0.70 \tag{18}$$

If major exergy destruction takes place upstream on a branch (i) of exergy flow:

$$\psi_{Ri} = \left(\frac{\varepsilon_{\text{dem}}}{\varepsilon_{\text{sup}}}\right)_i \tag{19}$$

or takes place downstream:

$$\psi_{Ri} = 1 - \left(\frac{\varepsilon_{\text{des}}}{\varepsilon_{\text{sup}}}\right)_i \tag{20}$$

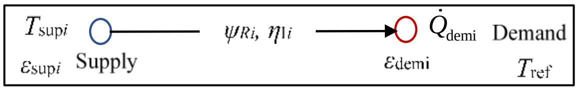


Figure 8. Supply-demand exergy flow in a single path (*i*) of a complex system

$$\bar{\Psi}_R = \frac{\sum_{i=1}^{j} \Psi_{Ri} \dot{Q}_{\text{dem}i} / \eta_{\text{I}i} \left(1 - \dfrac{T_{\text{ref}}}{T_{\text{sup}i}}\right)}{\sum_{i=1}^{j} \dot{Q}_{\text{dem}i} / \eta_{\text{I}i} \left(1 - \dfrac{T_{\text{ref}}}{T_{\text{sup}i}}\right)} \tag{21}$$

$$\eta_{\text{II}} = COP_{\text{EX}} = \bar{\psi}_R \eta_{\text{I}} \tag{22}$$

$$\varepsilon_{\text{des}} = 1 - COP_{\text{EX}} = 1 - \eta_{\text{II}} = 1 - \left(\eta_{\text{I}} \bar{\psi}_R\right) \tag{23}$$

If both η_{I} and ψ_R are one then ε_{des} is zero. If both η_{I} and ψ_R are zero then ε_{des} is one: all exergy is destroyed.

On a single exergy flow path in a complex system after using eq. (20):

$$\varepsilon_{\text{des}} = \varepsilon_{\text{sup}} \left(1 - \psi_R\right) = \varepsilon_{\text{sup}} \left(1 - \frac{\eta_{\text{II}}}{\eta_{\text{I}}}\right), \tag{24}$$

from eq. (23):

$$COP_{\text{EX}} = 1 - \varepsilon_{\text{des}} = 1 - \varepsilon_{\text{sup}} \left(1 - \psi_R\right) \tag{25}$$

$$\Delta CO_2 = 0.27 \varepsilon_{\text{des}} \ \text{kg CO}_2\text{/kWh of heat} \tag{26}$$

$$\sum CO_2 = \left(\frac{c}{\eta_{\text{T}}}\right) + 0.27 \varepsilon_{\text{des}} \quad \{\text{per unit heat}, Q\} \tag{27}$$

After neglecting transmission losses or temperature is peaked by an on-site boiler, such that if $\eta_T \sim \eta_I$.

$$\sum CO_2 \simeq \left(\frac{c}{\eta_I}\right) + 0.27\varepsilon_{des} \simeq c\left(\frac{COP_{EX}}{\bar{\psi}_R}\right)^{-1} + 0.27\varepsilon_{des}$$
$$= \left(\frac{c\bar{\psi}_R}{COP_{EX}}\right) + 0.27(1 - COP_{EX}) \tag{28a}$$

$$\sum CO_2 \simeq \left(\frac{c\bar{\psi}_R}{1-\varepsilon_{sup}(1-\bar{\psi}_R)}\right) + 0.27\left[1-1+\varepsilon_{sup}(1-\bar{\psi}_R)\right]$$
$$\simeq \left(\frac{c\bar{\psi}_R}{1-\varepsilon_{sup}(1-\bar{\psi}_R)}\right) + 0.27\left[\varepsilon_{sup}(1-\bar{\psi}_R)\right] \tag{28b}$$

$$\sum CO_2 \simeq \left(\frac{\dfrac{c\bar{\psi}_R}{\varepsilon_{sup}}}{\dfrac{1}{\varepsilon_{sup}} - (1-\bar{\psi}_R)}\right) + 0.27\left[(1-\bar{\psi}_R)\right] \quad \{\bar{\psi}_R > 0.70\} \tag{29}$$

$$d\varepsilon_{des} = \left(\frac{T_{ref}}{T_{sup}^2}\right) dT_{sup} \quad \{\text{see fig. 2}\} \tag{30}$$

$$\varepsilon_{des}(T_{sup}) = \frac{1}{2}\left(1 - \frac{T_{ref}}{T_{sup}}\right) \quad \{T_{sup} \ge T_{ref}\} \quad \{\text{must be minimized}\} \tag{31}$$

Tiers of the holistic model

There are four tiers, which establish the steps of dynamic optimization and control algorithm: TIER-1 – Renewable energy resource(s), TIER-2 – District energy supply plant, TIER-3 – Exergy transport between the plant and the district (city), and TIER-4 – Demand (customer) zone of the district energy system, including prosumer supply.

$$\dot{Q}_{sup} = \eta_I \dot{Q}_{res} + \dot{Q}_{pro} - \Delta\dot{Q}_{pro} - \Delta\dot{Q}_{sup} \tag{32}$$

$$E_{X\,sup} = \eta_{II} E_{Xres} + E_{Xpro} - \Delta E_{X\,sup} - \Delta E_{Xpro} \tag{33}$$

where $\eta_I \dot{Q}_{res}$ is the thermal power supply at the exit of the plant, $\dot{Q}'_{sup}$. The η_I is the overall First law efficiency The last two terms in eqs. (32) and (33) represent the exergy losses between plant and the district and η_{II} is the exergy efficiency. Thermal loss (gain) coefficients are assumed to be the same for heating and cooling pipes. The TIER-1 covers the energy sources available for the district. The TIER-2 covers energy conversion and storage systems. The TIER-3 covers the main piping system that connects the district plant and the built environment on both supply and return sides. The TIER-4 covers the built environment (City). The TIER at the same time correspond to four stages of the dynamic optimization and control algorithm, which is planned for the next step of this study. The algorithm starts backward from TIER-4 to TIER-1.

$$\Delta E_{X\mathrm{Lsup}} = x_1 L \left| 1 - \frac{T'_{\mathrm{sup}}}{T_{\mathrm{sup}}} \right| \Delta \dot{Q}_{\mathrm{sup}} \tag{34}$$

$$\Delta E_{X\mathrm{Lret}} = x_2 L \left| 1 - \frac{T'_{\mathrm{ret}}}{T_{\mathrm{ret}}} \right| \Delta \dot{Q}_{\mathrm{pros}} \tag{35}$$

Here, x_1 and x_2 are the heat loss coefficients per meter of pipe. This rule holds for TIER-4 piping:

$$\Delta T_{\mathrm{sup}} = T'_{\mathrm{sup}} - T_{\mathrm{sup}} = x_3 L \Delta \dot{Q}_{\mathrm{sup}} \tag{36}$$

$$\Delta T_{\mathrm{ret}} = T_{\mathrm{ret}} - T'_{\mathrm{ret}} = x_4 L \Delta \dot{Q}'_{\mathrm{pro}} \tag{37}$$

The TIER-1: Resources

This tier is a hybridization of different renewable and waste energy sources available for the district plant area (TIER-2). Each energy conversion system (i) like solar PVT or a wind turbine is defined in terms of their resource energy harvesting design capacity, $\dot{Q}_R(i)$ [kW], unit exergy, $\varepsilon(i)$ [kW/kW] supply temperatures (if applicable), chemical exergy (*i. e.* biogas from the district waste), energy conversion efficiency, η_{I} (i), embodied exergy $E_{X,\mathrm{m}}(i)$ [kWh/kW], embodied CO_2 [kWh/kW equivalent] and embodied cost for unit $\dot{Q}_R(i)$ [kW]. Embodied exergy and CO_2 costs must be returned by increased exergy rationality during operation. Sample exergy embodiments are given in tab. 1. The equivalent solar source temperature, $T_{\mathrm{f,solar}}$, and unit exergy, $\varepsilon_{\mathrm{solar}}$ for a given normal solar insolation, I_n is given by eq. (38). Equation (39) is the Carnot Cycle-Equivalent T_{f} for wind [8]:

Table 1. Sample list of wind turbine and solar PV embodiments [15]

RES	Embodied exergy	Unit
Wind turbine (6 MW electricity)	1.21	MJ/s of lifetime
Solar PV (157.2 m^2 PV block)	716	GJ/block
Solar PVT (160 m^2 block)	1200*	GJ/block

* Estimated value

$$\frac{I_{\mathrm{n}}}{1366\ \mathrm{W/m^2}} = \frac{\varepsilon_{\mathrm{solar}}}{\varepsilon_{\mathrm{e}}} = \frac{\left(1 - \dfrac{T_{\mathrm{ref}}}{T_{\mathrm{f,solar}}}\right)}{1\ \mathrm{kW/kW}} \quad \{\text{solar energy}\} \tag{38}$$

$$T_{\mathrm{f,wind}} = \frac{T_{\mathrm{ref}}}{(1 - 0.95\eta_{\mathrm{Iwt}})} \simeq \frac{T_{\mathrm{ref}}}{(1 - \eta_{\mathrm{Iwt}})} \quad \{\text{wind turbine}\} \tag{39}$$

The TIER-2: The central plant

All sustainable power and heat generating and energy conversion systems of (i) different types using renewables and waste heat are collocated and bundled. Prosumers are excluded. A new exergy benefit-to-embodied cost metric, which at the same time indexed to exergy destructions during annual operation, namely *EXBC* has been developed, using simulated hourly design data for the given location and sustainable systems to be involved:

$$EXCB = \left(\frac{1}{k}\right) \sum_{i=1}^{k} \frac{\int_{t=0}^{8760} \left[\dot{Q}_{Ri}(t) \eta_{\mathrm{I}i}(t) \left(\dfrac{\varepsilon_i(t)}{\varepsilon_{\mathrm{des}i}(t)} \right) \right] \mathrm{d}t}{\left[E_{X\mathrm{m}i} + E_{\mathrm{m}i} + \left(\dfrac{\overline{\eta}_{\mathrm{T}}}{\overline{c}_{\mathrm{f}}} \right) \mathrm{CO}_{2\mathrm{m}i} + \dfrac{1}{\overline{p}} C_{\mathrm{m}i} \right]} \quad \{\text{maximize}\} \tag{40a}$$

Here the denominator includes embodiments of exergy, energy, CO_2, and renewable system cost, C, respectively. Another constraint is the exergy-payback ratio of the total embodied exergy of the sustainable systems installed in the plant, $\Sigma E_{X,\mathrm{m}}$ *vs.* $E'_{X,\mathrm{sup}i}$, namely EMR for (i) different systems in the bundle. The goal is to keep EMR below 5 years, which is indexed to an annual capacity factor, CF_i of each renewable source (i) in TIER-1. Minimization is iterative with varying supply mix of renewables:

$$EMR = \frac{\sum E_{X\mathrm{m}i}}{8760\sum CF_i E'_{X\,\mathrm{sup}\,i}} < 5 \quad \{\text{constraint}\} \tag{40b}$$

$$\psi_R = 1 - \frac{\sum \varepsilon_{\mathrm{des}}}{\varepsilon_{\mathrm{s}}} = 1 - \frac{\left(1-\dfrac{350\text{ K}}{353\text{ K}}\right)+\left(1-\dfrac{318\text{ K}}{320\text{ K}}\right)+\left(1-\dfrac{315\text{ K}}{318\text{ K}}\right)+\left(1-\dfrac{283\text{ K}}{295\text{ K}}\right)}{\left(1-\dfrac{283\text{ K}}{638.8\text{ K}}\right)} = 0.88 \quad \{\text{see fig. 9}\}$$

According to tab. 2 PVT3 (fig. 10) has the highest ψ_R.

Table 2. Comparison of solar power, heat and power, and heat systems

FEATURE		SYSTEM			
		CSP	PV	PVT	PVT3
Efficiency η_I	Power	0.40	0.17	0.20	0.25
	Heat	0.35	–	0.55	0.65
ψ_R		0.726	0.64	0.79	0.88
$\varepsilon_{\mathrm{des}}$		0.344	0.198	0.094	0.055
ΔCO_2		0.093	0.053	0.025	0.015
Occupied area per MW_e		7.6 acres	4.4 acres	4.1 acres	3.4 acres

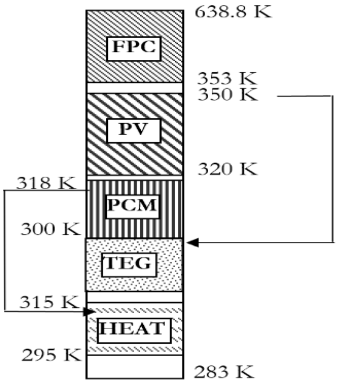


Figure 9. Exergy flow bar for PVT3

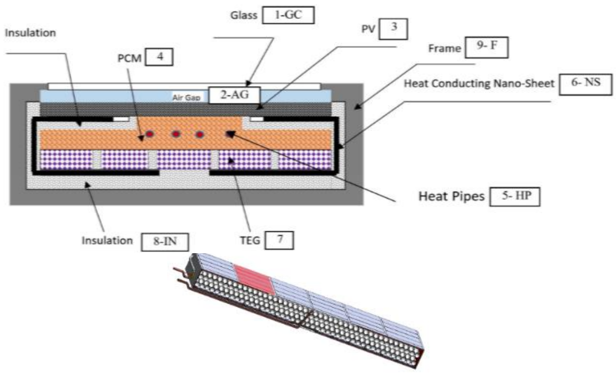


Figure 10. Solar PVT3 casette (TPI patent: 2017/10622)

The TIER-3 exergy transport between the plant and the city

Among many alternatives to supply exergy transport, the following three scenarios were selected:

– *Scenario 1, Electricity only:* Heating and cooling by local heat pumps (EU goal for total electrification for decarbonization). Yet additional electrical infrastructure and upgrading of power lines must be considered. An optimum on-site heat pump sizing, building insulation, and HVAC equipment oversizing may be required in TIER-4 to compensate for the performance loss of the equipment.
– *Scenario 2, Electricity and heat*: There is one main thermal network (piping) delivering heat only to the city. Cooling is achieved in the buildings by utilizing the heat supply in on-site ABS and ADS units. If there is a thermal power plant: temperature peaking at the plant with steam supply reduces power generation capacity. Otherwise, temperature peaking by heat pumps or building equipment oversizing or both at the city level. A dedicated and comprehensive model is presented, because in many cases this scenario is the most infrastructure, exergy, and carbon footprint-heavy.
– *Scenario 3, Electricity, heat, and cold*: Two district heating and district cooling networks. If the heating degree-hours value is dominant, then the cooling network may not be feasible and *Scenario 2* may be preferred. If there is a thermal power plant, then temperature peaking maybe with steam supply at an expense of reduced power. The exergy flow and pumping exergy balance per meter of pipe with known properties and the district course, gives a simple relationship:

$$\mathrm{d}E_{\mathrm{XP}} = \frac{\Delta E_{X\mathrm{P}}}{\Delta L} \tag{41}$$

$$L_{\max} < \frac{\dot{Q}_{\mathrm{sup}}\left(1-\dfrac{T'_{\mathrm{ret}}}{T'_{\mathrm{sup}}}\right)}{2\mathrm{d}E_{X\mathrm{P}}} \quad \{\text{one-way distance}\} \tag{42}$$

The term $\mathrm{d}E_{X\mathrm{PS}}$ in the denominator is the exergy demand of the pumping station(s) per unit distance. The new equation considers the average design flow velocity in the main district loop (One may replace 5 m/s by another input design value). From Affinity Laws [37]:

$$\frac{P_{X\mathrm{EL}}}{L} = c\frac{\dot{V}^3}{D^5}\left(\frac{1}{\eta_{\mathrm{P}}}\right)\left(\frac{1\ \mathrm{kW}}{1\ \mathrm{kW}}\right) \le \dot{Q}_{\mathrm{D}}\left(1-\frac{T_{\mathrm{DS}}}{T_{\mathrm{DR}}}\right) \tag{43}$$

where:

$$c = f\left(\frac{\rho}{g_{\mathrm{c}}}\right)\left(\frac{4}{\pi^2}\right) \tag{44}$$

Then solving for the maximum permissible distance from the plant to the district on average which can be assumed to be the half distance of the complete main district loop length, L:

$$L_{\max} \le \frac{\left(1-\dfrac{T_{\mathrm{DR}}}{T_{\mathrm{DS}}}\right)\eta_{\mathrm{P}}}{c\dot{Q}_{\mathrm{D}}}\left(\rho C_p \Delta T_{\mathrm{D}}\right)^2 D^5 \tag{45}$$

here:

$$\Delta T_{\mathrm{D}} = T_{\mathrm{DS}} - T_{\mathrm{DR}} \tag{46}$$

The pipe diameter, D, is governed by practical flow velocity, *i. e* 5 m/s:

$$L_{\max} \leq \frac{\left(1-\dfrac{T_{\mathrm{DR}}}{T_{\mathrm{DS}}}\right)\eta_{\mathrm{P}}}{c\dot{Q}_{\mathrm{D}}}\left(\rho C_p \Delta T_{\mathrm{D}}\right)^2\left(\frac{4\dot{Q}_{\mathrm{D}}}{5\pi\rho C_p \Delta T_{\mathrm{D}}}\right)^{5/2} = \frac{\left(1-\dfrac{T_{\mathrm{DR}}}{T_{\mathrm{DS}}}\right)\eta_{\mathrm{P}}}{c}\dot{Q}_D^{1.5}\frac{32}{\sqrt{5\pi\rho C_p \Delta T_{\mathrm{D}}}} \tag{47}$$

– *Scenario 4, Central Temperature Peaking*: Large heat pumps peak the temperature at the plant. Although larger heat pumps are cheaper per unit capacity, district heating piping diameter is smaller with larger ΔT, and equipment oversizing is reduced, larger TES systems are required at the plant and if district cooling is required, different heat and cold distribution regimes necessitate a separate cooling network.

Comparison of the scenarios

A new metric has been developed, *TVAR*, which stands for total value-adding potential ratio per unit electric power generated at the renewable energy plant of the district. The *TVAR* compares this unit power with the final total added value supplied to the district in terms of the sum of power and thermal exergy:

$$TVAR = \frac{\text{Total exergy supplied to the district}}{\text{Unit electric exergy originally generated}} = \frac{x\eta_{\mathrm{H}}\left(1-\dfrac{T_{\mathrm{ret}}}{T_{\mathrm{sup}}}\right)+(1-x)\times 0.95\eta_{\mathrm{T}}}{1\times 0.95} \quad \{1 \geq x \geq 0\} \tag{48}$$

The split between the thermal and the electrical supply to the grid, x represents the aforementioned scenarios. The condition $x = 0$ is *Scenario 1* (Only electricity is delivered to the district. $x = 1$ represents *Scenario 2* (Only heat is delivered to the district). Equation (49), shows that $L_{\max}$ is an implicit function of *TVAR*, which establishes another upper limit for $L_{\max}$. Table 3 summarizes typical results for four scenarios:

Table 3. Typical *TVAR* values of the *Scenarios* for the same $L_{\max}$

Scenario	*TVAR*
1	0.95
2	0.92
3	0.89
4	0.85

$$TVAR = \frac{0.1x\left\{\left[\left(\dfrac{c}{\eta_{\mathrm{P}}}\right)L_{\max}\right]^{2/3}\left(5\pi\rho C_p \Delta T_{\mathrm{D}}\right)^{1/3}\right\}+(1-x)\times 0.95\left[\eta_{\mathrm{T}} f(L_{\max})\right]}{1\times 0.95} \tag{49}$$

The TIER-4, The city

While the conglomeration of on-site heat pumps may be costlier, district infrastructure costs are saved. [33-35]**.** Therefore, the solution starts from LowEx buildings such that thicker the building insulation, t is, lower the heating or cooling loads are. This means less thermal power, $\dot{Q}_{\mathrm{o}}$, low exergy demand, $\varepsilon_{\mathrm{dem}}$, better *COP*, temperature peaking demand, leading to a decrease in other investment and operating costs, and embodiments. Equation (50) is the first solution:

$$T_{\sup 2} = \sqrt[n]{\frac{\left(\dot{Q}_{\mathrm{o}} - bt\right)}{c}} + T_{\mathrm{a}} \tag{50}$$

If $T_{\sup 2}$ exceeds the value permitted in eq. (6) then this equation shall be used. Radiant panel heating and cooling systems offer two advantages: First, they are more responsive to very moderate supply temperatures. Second, n is close to one, which makes the control more linear [33]. A trivial solution is $t_{\mathrm{opt}} = \dot{Q}_{\mathrm{o}}/b$, and $T_{\mathrm{su2p}} \to (T_{\mathrm{a}} - T_{\mathrm{g}})$. For maximizing ψ_R, the next step with the ground reinjection temperature, T_{g} as the reference and electricity supplied by a natural gas power plant, is an exergy flow diagram, fig. 11.

$$\psi_R = \frac{\left(1 - \frac{T_{\mathrm{g}}}{T_{\sup}}\right) COP}{\left(1 - \frac{T_{\mathrm{g}}}{2235}\right)} = \frac{\left(1 - \frac{T_{\mathrm{g}}}{T_{\sup}}\right)}{\left(1 - \frac{T_{\mathrm{g}}}{2235}\right)} \left[q - r\left(T_{\sup} - T_{\mathrm{g}}\right)\right] = \frac{\left(1 - \frac{T_g}{\sqrt[n]{\left(\frac{\dot{Q}_o - bt}{c}\right)}}\right)}{\left(1 - \frac{T_{\mathrm{g}}}{2235}\right)} \left[q - r\left(\sqrt[n]{\left(\frac{\dot{Q}_o - bt}{c}\right)} - T_{\mathrm{g}}\right)\right] \tag{51}$$

$$t_{\mathrm{opt}} = \left(\frac{\dot{Q}_o - c\left|T_{\sup} - T_a\right|^n}{b}\right) \quad \left\{\text{with } \frac{\mathrm{d}\psi_R}{\mathrm{d}t} = 0\right\} \tag{52}$$

$$COP_{\mathrm{EX}} = \frac{\left(\dot{Q}_{\mathrm{o}} - bt\right)\left|1 - \frac{T_{\mathrm{ref}}}{T_{\mathrm{a}}}\right|}{\frac{\left(\dot{Q}_{\mathrm{o}} - bt\right)}{\left(q - r\left|T_{\sup 2} - T_{\mathrm{g}}\right|\right)} \times 0.95 + \sum E_{XP} \times 0.95 + \left(\dot{Q}_{\mathrm{o}} - bt\right)\left|1 - \frac{T_{\mathrm{ref}}}{T_{\mathrm{g}}}\right|} \quad \{\text{maximize}\} \tag{53}$$

Increasing COP leads to environmental and cost benefits while a smaller heat pump has less investment cost, ΔI_{HP}, and longer operating hours close to peak efficiency. A payback period, T_{pb} is determined by comparing the additional net investment cost $\Delta I = (\Delta I_{\mathrm{ins}} - \Delta I_{\mathrm{HP}})$, and the net operational savings, $S(t)$, fig. 12:

$$S(t) = \bar{p}\left(\frac{\dot{Q}_{\mathrm{o}}}{\Delta COP}\right) t \tag{54}$$

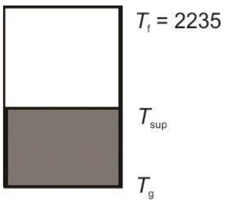


Figure 11. Exergy flow bar for electric-driven heat pump, electricity is from NG thermal plant

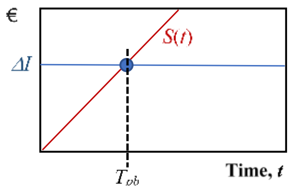


Figure 12. Additional net investment cost *vs.* net operational savings of a heat pump

Holistic model

The holistic model is an expanded version of the COP_{EX} equation for TIER-4:

$$COP_{\mathrm{EX}} = \frac{E_{X\,\mathrm{sup}} + E'_{X\mathrm{pro}}}{\dfrac{\left(\dot{Q}_{\mathrm{o}} - bt\right)}{\left(q - r\left|T_{\mathrm{sup}} - T_g\right|\right)} \times 0.95 + \sum E_{X\mathrm{P}} \times 0.95 + E_{X\mathrm{res}} + E_{X\mathrm{pro}}} \quad \{\mathrm{maximize}\} \tag{55}$$

The COP_{EX} may be maximized iteratively by changing variables. $E'_{X\mathrm{pro}}$ is the part of the prosumer exergy generation, $E_{X\mathrm{pro}}$ supplied to the district. Figure 13 gives a sample dependence of COP_{EX} on T_{sup} for different insulation thicknesses, t. The optimum T_{sup} does not change with t in this specific case. The dependence of COP_{EX} at thinner insulations diminishes with T_{sup} exceeding T_{supopt}.

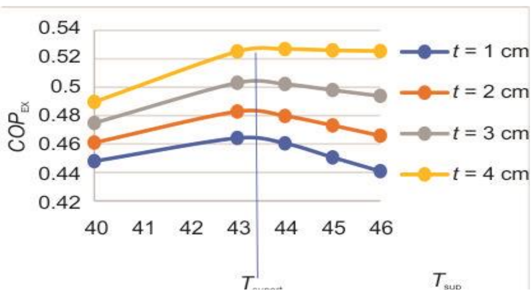


Figure 13. Change of COP_{EX} with T_{sup} and t

Discussion

This paper has dealt with the exergy-based optimum design and operation scheme of district energy systems, deemed to be necessary to be based on a holistic view, covering all phases starting from the renewable energies at their source, then including the energy conversion and storage plant feeding the district energy network, and finally the buildings in the district. For low temperature applications, which enable us to harvest low-exergy renewables and waste thermal energy, all which remained almost unexploited so far, it has been pointed out that a careful and precise exergy balance between each step of the district supply and the demand points is essential. A holistic model was developed with an objective function of maximizing the exergy-based COP, namely COP_{EX} for the entire system. The REMM was utilized in deriving the essential relationships for defining and connecting the COP_{EX} value with exergy destructions and CO_2 emissions, such that while COP_{EX} is maximized, the carbon footprint is minimized in terms of minimizing the exergy imbalances between all steps of district heating. The model is also valid for district cooling systems. In deriving LowEx buildings, the optimum insulation thickness was also included in the maximization process of COP_{EX}. Results showed that maximum COP_{EX} does not depend much on the district supply temperature. This relaxes the constraints on determining the optimum district supply temperature and the maximum permitted distance, L_{max} between the plant and the city.

Conclusions

The 5G district energy systems are a promising asset against climatic urgency but at the same time, more prone to climatic hazards [38]. According to the IPCC Report, the global average surface temperature increases exponentially [39]. Low-exergy districts and exergy-matching buildings, all holistically designed and controlled with the second law increase the overall REMM efficiency, ψ_R, reduce *GWP* and *ODP* to such an extent that natural decarbonization may take over [40]. Therefore low-exergy district energy systems, when coupled with LowEx buildings, seem to have a big potential for decarbonazion, provided that such attempts are accompanied by the following auxiliary recommendations.

- In a district energy system, customers may receive and return heat or cold at different temperatures. Therefore, development and use of exergy meters and thermal pulse meters will be prudent [4].
- Electric motor efficiencies higher than 0.90 (> IE4) and high-efficiency pumps [41].
- Solar PVT panels covering almost all solar spectrum [42-44].
- Switching to direct-current power supply. Wind and solar power are originally direct-current and then inverted to AC, and then converted to direct-current again in many uses like computers.
- Exergy budgeting for all components of district energy, including thermal energy storage.
- High efficiency wind turbines like direct-drive systems should be considered [45].
- The optimum number of building floors in urban development is important in such a manner that pumping exergy is related to $L_{\max}$, thus to the average number of building floors [46].
- Although each renewable source has their energy atlases [47], their different unit exergy make it difficult to overlay them to calculate their composite exergy supply potential. Therefore exergy-composite atlases are needed.
- Supplementary temperature-peaking systems, like fossil fuel-fired boilers, must be analyzed with their embodiments, CO_2 and *ODI* responsibilities, and exergy rationality.

Nomenclature

b – coefficient of thermal load dependence on building insulation thickness [–]
ALT – residence time in the atmosphere [year]
c – CO_2 content of the fuel [kg_{CO2}/kWh], eq. (27)
$\overline{c}_f$ – CO_2 content of the fuel mix in a given energy sector [–]
c – heating capacity of the equipment [kW/K$^{-(1/n)}$], eq. (7)
C – coefficient of the pumping power exergy demand, eq. (4)
C_p – specific heat [kJkg^{-1}K^{-1}]
C_{HP} – life cycle cost of heat pump oversizing [€/kWh]
C_{eq} – life cycle cost of equipment oversizing [€/kWh]
C_1 – heat pump temperature coefficient at design conditions [K]
C_2 – equipment temperature coefficient at design conditions [K]
ΔCO_2 – avoidable CO_2 emission [kg_{CO2}/kWh]
COP_{EX} – exergy-based coefficient of performance [–]
D – pipe inside diameter [m]
E_X – exergy [kW]
g_c – acceleration of gravitation =9.81 [m/sec^2]
I_n – solar energy intensity normal to the collector surface plane [W/m^2]
ΣL – total trip distance of the supply and return main piping [m]
L – straight distance between the central plant and the district center [m]
$L_{\max}$ – allowable straight distance between the plant and the district [m], [km]
N_{HP} – number of identical heat pumps in tandem [–]
$NetE_{X\sup}$ – difference between supply power exergy and total pumping exergy[kW]
ODI – composite ozone-depletion index, eq. (1)
$\overline{p}$ – unit cost of a renewable energy system [kW]
q, r – constants of the linearized heat pump *COP*, eq.(9)
Q – thermal energy [kWh]
$\dot{Q}_D$, $\dot{Q}_{\sup}$ – thermal power of the district energy system at the plant exit [kW]
$\dot{Q}'_D$, $\dot{Q}'_{\sup}$ – thermal power of the district energy system at the district entrance [kW]
$\dot{Q}_o$ – original building thermal load before insulation [kW]
S – net operational savings [€]
T – temperature [K]
T_{DR} – average district loop return temperature in the main return pipe [K]
T_{DS} – average district loop supply temperature in the main supply pipe [K]
$T_{\sup 2}$ – district main piping supply temperature after temperature-peaking [K]
x – split between the thermal supply and electrical supply to the grid [–]

Greek symbols

ρ – mass density [kg/m^3]
$\overline{\Psi}_R$ – overall exergy management efficiency [–]
ΔP – pressure drop [Pa]
ΔT – supply and return temperature difference [K]

Subscripts or superscripts

a – air (indoor)
e – electricity
D – district
DR – district return side in the main district pipe
DS – district supply side in the main district pipe
dem – demand
des – destroyed (exergy)
f – Carnot cycle-equivalent source temperature-related
g – ground (geothermal)
H – heat
HP – heat pump
i – index for a branch in a multiple exergy-flow system
ins – thermal insulation
k – number of different renewable energy systems in the plant
m – embodied
min – minimum
max – maximum (allowable)
opt – optimum
p – pump (pump station)
pb – pay-back related variable
res, ret – resource, return
solar – solar energy system
sup – supply
T – power transmission-related
wind – wind energy system
X, *EX* – exergy
wt – wind turbine
n – equipment thermal output coefficient

Acronyms

ABS, ADS – absorption and adsorption cooling
CHP – combined heat and power
CSP – concentrating solar power
DE, DH, DC– district energy, heating, cooling
EBC – energy in buildings and communities program
HP – heat pump
IE4 – super-premium efficiency according to IEC/EN 60034-30-1:2014
IEA – International Energy Agency
IPCC – intergovernmental panel on climate change
LowEx – low exergy (building, source, or district)
PV – solar photovoltaic
PVT – solar photovoltaic-thermal
100REXC – hundred-percent renewable exergy city
RHC – renewable heating and cooling
TPI – Turkish Patent Institute

Reference

[1] ***, EC, 2030. Climate & Energy Framework; Climate Strategies & Targets; European Commission: Brussels, Belgium, https://ec.europa.eu/clima/policies/strategies/2030_en
[2] Gawer, R., Cezarz, N., Stanford University: Economic, Efficient, Green District Low Temperature Hot Water, IDEA Annual Conference, Detroit, Mich., USA, 2016
[3] ***, UNEP, 2015. District Energy in Cities, Unlocking the Potential of Energy Efficiency and Renewable Energy, UNEP DTIE Energy Branch http://wedocs.unep.org/bitstream/handle/20.500.11822/9317/-District_energy_in_cities_unlocking_the_potential_of_energy_efficiency_and_renewable_ene.pdf?sequence=2&isAllowed=y
[4] Kilkis, B., Barriers, Solution and Metrics for 100% Renewable Cities, Special Report to ETIP RHC Meeting, Brussels, Belgium, 2020
[5] ***, http://www.relatedproject.eu/demonstrations/
[6] ***, RHC 2014. Cross-Cutting Technology Roadmap-European Technology Platform on Renewable Heating and Cooling, EC, Brussels
[7] ***, EWG. 2019. New Study: Global Energy System based on 100% Renewable Energy, 12 April. http://energywatchgroup.org/new-study-global-energy-system-based-100-renewable-energy
[8] Kilkis, S., Energy System Analysis of a Pilot Net-Zero Exergy District, *Energy Convers. Manag.*, *87*, (2014), Nov., pp. 1077-1092
[9] ***, EBC. Annex 64-LowEx Communities, https://www.iea-ebc.org/projects/project?AnnexID=64
[10] ***, EC, 2018. Final Report of the High-Level Panel of the European Decarbonization Pathways Initiative, ISBN 978-92-79-96827-3, Publications office of the EU: Luxembourg
[11] Gong, M., Werner, S., Mapping Energy and Exergy Flows of District Heating in Sweden, *Energy Procedia*, *116*, (2017), June, pp.119-127 https://www.researchgate.net/publication/318201324_Mapping_energy_and_exergy_flows_of_district_heating_in_Sweden
[12] Harvey, D. L. D., *A Handbook on Low-Energy Buildings and District-Energy Systems, Fundamentals, Techniques, and Examples*, Earthscan, London, UK, 2012
[13] Fischedick, M., *et al.*, The Role of Hydrogen for the Long-Term Development of Sustainable Energy Systems-a case study of Germany, *Sol Energy*, *78*, (2005), 5, pp. 678-686

[14] Kilkis, B., Kilkis, S., Hydrogen Economy Model for Nearly Net-Zero Cities with Exergy Rationale and Energy-Water Nexus, *Energies, 11* (2018), 5, 1226
[15] Dincer, I., Rosen, M. A., *Exergy-Energy, Environment and Sustainable Development*, Elsevier, New York, USA,2013
[16] De Rossi, L., *et al*., Smart Heat Pump, Using Sea Water for Urban Renewal Project, *ASHRAE J., 58* (2016) 4, pp. 68-74
[17] Lund, H., *Renewable Energy Systems: A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions,* Academic Press, Elsevier, Massachusetts, USA, 2014
[18] ***, Bioenergy Int. 2019. Fortum Värme Changes name to Stockholm Exergi, https://bioenergyinternational.com/heat-power/fortum-varme-changes-name-stockholm-exergi
[19] ***, BINE Information Service. 2018. District Heating Network Becomes Heat Hub, Projectinfo 02/2018, Federal Ministry of Economic Affairs and Energy (BMWi) ISSN 0937-8367
[20] Prando, P., *et al.,* Analysis of the Energy and Economic Impact of Cost-Optimal Buildings Refurbishment on District Heating Systems, *Sci Technol Built Environ, 21,* (2015), 6, pp. 876-891
[21] Wang, H., *et al*., Optimizing the District Heating Primary Network from the Perspective of Economic-Specific Pressure Loss, *Energies*, *10* (2017), 8, 1095
[22] Kavvadias, K. C., Quoilin, S., Exploiting Waste Heat Potential by Long Distance Heat Transmission: Design Considerations and Techno-Economic Assessment, *Appl. Energy*., *216* (2018), Apr., pp. 452-465
[23] Ljubenko, A., *et al.*, Performance Analysis of a District Energy System, *Energies*, *6*, (2013), 3, pp. 1298-1313
[24] Verda, V., *et al*., A Thermodynamic Approach for the Analysis of District Heating Systems, *Int. J. Appl. Thermodyn.*, *4,* (2001), 4, pp. 183-190
[25] Sangi, R., Muller, D., Application of the Second Law of Thermodynamics to Control: A Review, *Energy*, *174,* (2019), May, pp. 938-953
[26] Kilkis, I. B., Closed Loop Versus an Open Loop District System: A Techno-Economical Assessment, Geothermal Resources Council, *Transactions of Geothermal Development of the Pacific Rim, 20*., (1996), pp. 95-102
[27] Kilkis, I. B., Rational Use and Management of Geothermal Energy Resources, *Int. J. Glob. Energy Issues*, *17,* (2002), 1-2, pp. 954-7118
[28] Kilkis, B., Kilkis, Ş., Rational Exergy Management Model for Effective Utilization of Low-Enthalpy Geothermal Energy Resources, *Hittite J. Sci. Eng.*, 5, (2018), Jan., pp. 59-73
[29] Kilkis, B., Exergy-Optimum Coupling of Heat Recovery Ventilation Units with Heat Pump in Sustainable Buildings, *Journal of Sustainable Development of Energy, Water and Environment Systems, 8, (2020)*, 4, pp. 815-845
[30] Kilkis, I. B. Rationalization and Optimization of Heating Systems Coupled to Ground-Source Heat Pumps, ASHRAE T., *106,* (2000), 2, pp. 817-822
[31] Kilkis, I. B., Rationalization of Low-Temperature to Medium-Temperature District Heating, ASHRAE T., *104,* (1998), 2, pp. 565-576
[32] Biyikoglu A., Kilkis, B., Thermodynamic Limits for Buildings: Energy vs Exergy, Proceedings, ASHRAE Winter Meeting, Seminar Presentation, ASHRAE: Atlanta, Geo., USA
[33] Kilkis, B., Exergy Metrication of Radiant Heating and Cooling, *ASHRAE T*., *117,* (*2011*), 1, pp. 442-449
[34] Kilkis, I. B., An Exergy Aware Optimization and Control Algorithm for Sustainable Buildings, *Int. J. Green Energy, 1,* (2004), 1, pp. 65-77
[35] Kilkis, I. B., An Analytical Optimization Tool for Hydronic Heating and Cooling with Low-Enthalpy Energy Sources, *ASHRAE Trans.*, *108,* (2012), 2, pp. 988-996
[36] Kilkis, B., Exergy-Rational and Carbon-Neutral Readiness for 5G Solar District Heating with Optimum Equipment Oversizing and Tandem Heat Pumps, Proceedings, ISEC 2020 Conference, Graz, Austria
[37] Ford, R. W., Affinity Laws, Why They Work and When They Don't, Technical Feature, *ASHRAE J*, (2011), pp. 42-43
[38] Aijazi, A. N., Brager, G. S., Understanding Climate Change Impacts on Building Energy Use, *ASHRAE J*, (2018), Oct., pp. 24-32
[39] Stocker, T., *et al.*, Climate Change 2013: The Physical Science Basis, 5^{th} Assessment Report of the IPCC, Cambridge University Press, Cambridge, UK
[40] Kilkis, B., Energy Consumption and CO_2 Emissions Responsibility of Airport Terminal Buildings: A Case Study for the Future Istanbul Airport, *Energy Build., 76,* (2014), June, pp. 109-118
[41] ***, VoltPro. 2019. High-Efficiency Industrial Motors, http://voltmotor.com.tr/en/voltpro/

[42] Narducci, D., *et al*., 2018. Photovoltaic-Thermoelectric-Thermodynamic Co-Generation, Chapter in: *Hybrid and Fully Thermoelectric Solar Harvesting,* Springer Series in Materials Science, New York, USA
[43] Kilkis, B., Optimum Operation of Solar PVT Systems: An Exergetic Approach, *Proceedings*, Solar TR2016 Conference and Exhibition, Paper No: 0025, Istanbul, Turkey, 2016, pp. 72-79
[44] ***, ASHRAE. New System Combines Solar Energy Technologies for Improved Efficiency, *ASHRAE J*., *58* (2016), 9, 6
[45] Kilkis, I. B., Utilization of Wind Energy in Space Heating and Cooling with Hybrid HVAC Systems and Heat Pumps, *Energy Build*., *30* (1999), 2, pp. 147-153
[46] Kilkis, S., Kilkis, B., An Urbanization Algorithm for Districts with Minimized Emissions Based on Urban Planning and Embodied Energy Towards Net-Zero Exergy Targets, *Energy*, *179*, (2019), July, pp. 392-406
[47] Moller, B., *et al*., Heat Roadmap Europe: Identifying Local Heat Demand and Supply Areas with a European Thermal Atlas, *Energy, 158*, (2018), Sept., pp. 281-292

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