EXERGY EFFICIENCY IS A KEY PERFORMANCE INDICATOR TO RANK ADVANCED ACTIVE ENERGY TECHNOLOGIES AT THE DISTRICT LEVEL

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ABSTRACT

Supplying electricity, heat and cold is an essential part in the development of more sustainable city districts. Previous papers have illustrated the interest of using the exergy efficiency concept to decompose the problem and rank the technology combinations according to their overall efficiencies. The idea of this paper is to extend these considerations to technology alternatives with a focus on two innovative technologies. The first one is very low temperature District Heating and Cooling (DHC) supplying directly air-conditioning needs as well as heating needs via local heat pumps. It is part of what is called fifth generation DHCs or "anergy networks" and based on water or, better, on CO_2 heat transfer fluid. The second one is hybrid SOFC-GT cogeneration units with or without CO_2 separation to supply electricity to the various users in the network including the decentralized heat pumps, while optimizing the heat recovery. The former allows a full synergy between heat providers and users and allow to design districts without cooling towers or chimneys except at one energy balancing plant, ideally close to a surface water energy source or sink.

Starting with the composite curves generated from a GIS survey of a given district, the analysis provides an estimate of the performance of standard 3 or 4th generation DH supplying heat at a temperature of 85°C with a CO_2 based fifth generation DHC delivering an energy source or sink at about 14°C and having an efficient SOFC-GT cogeneration unit somewhere on the network. Such advanced district energy system illustrates the power of using exergy efficiency indicators to judge on the efficiency increase in the use of the energy resources. This is done with a decomposition of the system in subsystems, as was previously published in a similar context but with more conventional technologies. The possibility of separating CO_2 from the effluents of the cogeneration system is also accounted for and this can only be coherently done by using exergy considerations.

1 INTRODUCTION

There is a large consensus that the world needs to curb its greenhouse gas (GHG) emissions. As shown by the international Energy Agency (IEA) as early as in their 2009 outlook report (IEA, 2009), energy efficiency is key to achieve this goal. In that report the relative contribution of increased efficiency was even more important than renewables, nuclear and Carbon Capture and Storage (CCS) considered separately. Of course, energy efficiency is a broad domain and major inefficiencies do exist today. One problem is the fact energy efficiency is still too often based on First Law considerations (energy effectiveness (Favrat and Kane, 2023)) only that do not consider the full potential of an efficient use of resources. The main reason is the backlog of old technologies, like fuel boilers or present nuclear reactor of generation up to 3, that contaminates the thinking of practitioners afraid of using more coherent indicators like the exergy efficiency. As indicated in (Borel and Favrat, 2010) domestic fuel boilers have exergy efficiencies of the order of 7%. Present nuclear reactors up to generation 3 have indeed an exergy efficiency of less than 1% considering all the fuel potential lost in the nuclear waste and that can be recovered in more advanced technologies like molten salt reactors of 4th generation (Tani *et al.*, 2010).

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With a growing population leaving in cities, urban areas have a large potential for exergy efficiency improvements. Global warming as well as the phenomena of heat islands are reinforcing the needs for cooling even in central to northern areas where mainly heating was of concern until recently. The multiplication of data centers with cooling needs but also opportunities for waste heat recovery is also changing the situation.

Independently from passive improvements of the building envelope, synergies between users through heating and cooling networks as well as the exploitation of novel active technology approaches of co- or tri-generation is to be considered and quantified. This paper focusses on some of the more advanced energy technologies in urban areas and their ranking in terms of exergy efficiency.

2 DISTRICT HEATING NETWORKS

District heating and cooling (DHC) is expected to be of growing interest in limiting pollution, both local and global, while maintaining or further developing energy services. With the growing trend of electrification ***tri-generation***, i.e. heating, cooling and electricity combined generation, is also progressing.

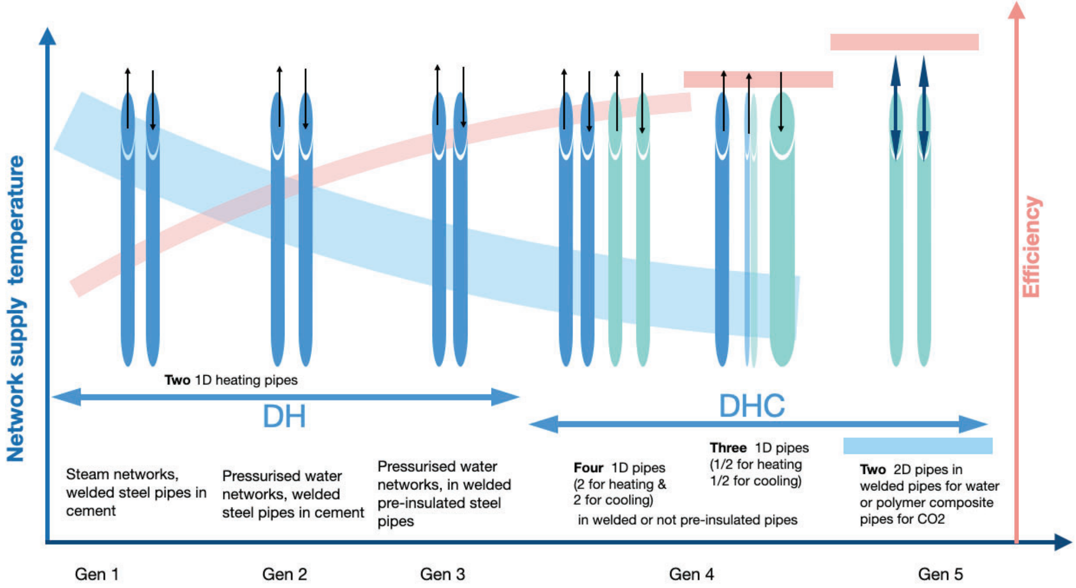

Figure 1: Generations of DH(C) networks, modified from (Lund *et al.*, 2014)

Industrialized countries and their cities have been, and still are, major contributors to Greenhouse Gas emissions. The first District Heating DH systems started from the 1880th in USA using steam as the heat transfer fluid. This technology was later replaced by pressurized water. (Lund *et al.*, 2014) proposed to classify DH(C) systems in 4 generations with a gradual transition from steam-based DH (Gen 1) to pressurized superheated water DH (Gen 2), to DH with unpressurized water in pre-insulated pipes (Gen 3), and finally to DHC networks integrating more energy functions with a gradually decreasing temperature level (Gen 4) (Figure 1).

A fifth generation has been introduced by several authors with different definitions, raising some controversy (Lund *et al.*, 2021).

To be pragmatic, we propose here the following definitions:

- 4th generation: DHC with more than 2 one-directional pipes at relatively low operating temperatures (<70°C). The most common:
  - 4th generation networks include 4 pipes, two for heating and two for cooling.
  - 3 pipe networks can also be considered of the 4th generation, with one pipe switching temperature between winter and summer to better cope with the needs (authors Avis, 2014). A three-pipe system is, for example, used in the city of Nanterre in France

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(ARTE, 2017) although only for heating with 65°C supply in one pipe and a 45°C supply in a second pipe and one single pipe for the return flow to the heating plant. The latter is equipped with a heat pump and a separate piping system collecting low temperature energy from sewage pipes to feed the evaporator. Another example is the cogeneration and heat pump energy plant of EPFL (Pelet *et al.,* 1998) with two networks leaving the plant, one at 65°C and one at 45°C. Before being recently renewed the plant was equipped with two NH_3 heat pumps fed with lake water at the evaporator plus a pipe delivering cold water from the lake for cooling with a simple discharge to the sewage system to avoid having a return pipe of the cooling network. The same structure was mainly kept with new NH_3 heat pumps in a new building.

- 5th generation: networks with ***two-pipe bidirectional networks operated close to ground level temperatures,*** satisfying both heating via local heat pumps and cooling either directly or via local refrigeration units. This last generation, sometimes called *anergy*[1] *networks*, can be subdivided into:
  - **water** networks with small differences of temperatures between supply and return with the challenge of requesting large pipes and significant pumping losses (Bunning *et al.*, 2018)
  - **CO_2** network (Henchoz *et al.*, 2015) using the latent heat of this heat transfer fluid without significant changes of the temperature level. With CO_2 these DHC networks need to be pressurized between 35 to 50 bars to be in the temperature range of 0 to 15°C necessary to allow direct cooling services.

Marginal one pipe water networks with one-way circulation and various supply sources and thermal storages, like studied in Melbourne (Vecchi *et al*., 2021) could also be considered in the 5th generation. They count on a balance between heat and cold users along the network with thermal storages on the way and potential air towers (cooling or supply to heat pumps for heating) to correct for load unbalance. 5th Gen DHC networks are also referred with the following different terminologies "bidirectional low temperature networks (Bunning *et al.,* 2018), low-temperature district heating and cooling networks (Ruesch and Haller, 2017) or balanced energy networks (Song *et al.,* 2019).

3 HYBRID FC-GT COGENERATION

In urban areas where the main needs are for electricity, heat and cold, cogeneration has been popular mainly in connection to large DHC with relatively high supply temperature typical of Gen1 and 2 DH. More recently and coming from the lower power scale emerged the Solid Oxide Fuel Cells (SOFC) and their hybrid SOFC-GT counterpart with higher electrical efficiencies and negligible health-affecting emissions. SOFC at their high temperature of operation have the great advantage of letting only oxygen ions go through the membrane from the cathode to the anode and are therefore less sensitive to the quality of fuels. They also do not require expensive catalysts. They can be designed with either cylindrical or planar cells although the latter tend to dominate the present trend. Pre-reformed natural gas or biogas or Synthetic Natural Gas SNG are usually the fuel for those cells that can oxidize both hydrogen (H_2) and carbon monoxide (CO). Since many cities are equipped with NG networks, those could be used to supply cogeneration units instead of being deconditioned along the wave of decarbonization of the cities. However, and to compare with other decarbonizing approaches, CO_2 capture and the collection and transport to a point of use or disposal is to be envisaged.

There are two main types of hybrid SOFC-GT. Figure 2a shows the integration with a pressurized SOFC that typically favors the use of a SOFC with tubular cells or a planar one which would require a pressurized enclosure. However, the anodic and cathodic streams are mixed at the exit of the SOFC and

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[1] Anergy is the name given to the part of energy that cannot be converted into work with the relation energy = exergy + anergy. This term has been used to describe DHC Gen 5 networks since these ones allow an easy use of waste or environmental heat.

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this impairs attempts to later capture CO_2 downstream. Since one significant interest of SOFC is that their process is inherently a separator of oxygen and other components of air like nitrogen, it is important, in these fuel cell designs, to keep separate at the exit the anodic and cathodic streams. The anodic stream is made of steam, CO_2 and remaining fuel, basically H_2. Capitalizing on this advantage (Facchinetti et al., 2011) introduced other concepts coupling atmospheric planar FC stacks with sub-atmospheric GT (inverted Brayton cycle) and CO_2 capture (Figure 2b). The interest of the latter is that the inverted Brayton cycle expands the whole anodic flow in the turbine and compress only the remaining gas after condensation in a cooler. The condensed water is separately pumped with a much low energy requirement than would be required to recompress steam. Typically, the anodic gas exhaust temperature from the fuel cell is in the range of 780 to 900°C. The remaining fuel in the anodic gas flow is characterized by a fuel utilization factor that is in the range of 80 to 95%. The remaining fuel is to be typically burned in a burner that can be fed by air or preferably by pure oxygen to keep the CO_2 and H_2O concentrations in the gas as high as possible to favor an efficient separation.

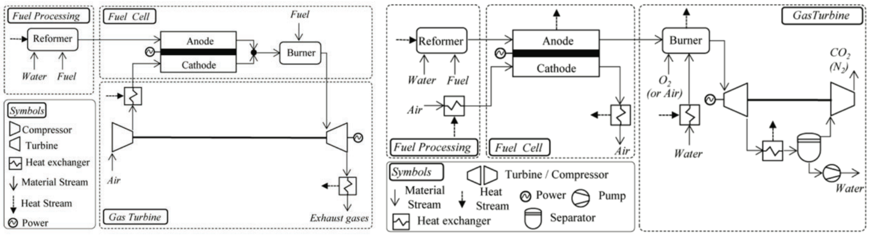

Figure 2: Hybrid SOFC-GT concepts with a) pressurized SOFC and b) atmospheric SOFC with one sub-atmospheric gas turbine on the anodic exhaust (Facchinetti *et al*., 2011)

(Facchinetti *et al.*, 2011) show an exergy efficiency close to 70% with a power part of the gas turbine of the order of 16%. Even if such efficiencies are already better than those of the most advanced centralized combined cycle plant, they showed that by adding another gas turbine on the cathodic exit flow as well would further add to the exergy efficiencies.

As proposed earlier (Facchinetti *et al.,* 2011) the exergy efficiency for the general cogeneration case with oxy-combustion at the burner and CO_2 separation with recompression of the CO_2 to atmospheric pressure can be written as:

$$\eta = \frac{\dot{E}_{GT}^{-}+\dot{E}_{SOFC}^{-}+\dot{E}_{Y\,CO_2}^{-}+\dot{E}_{Y\,water}^{-}-\dot{E}_{water\,pump}^{-}+\dot{M}_{CO_2}\,e_{d\,CO_2}}{\dot{E}_{y\,comb}^{+}+\dot{M}_{O_2}^{+}\,e_{d\,O_2\,burner}} \tag{1}$$

This equation uses the formalism adopted in (Borel and Favrat, 2010), where $\dot{E}_{GT}^{-}$, $\dot{E}_{SOFC}^{-}$, $\dot{E}_{water\,pump}^{-}$ are electric powers and $\dot{E}_{Y\,CO_2}^{-}$, $\dot{E}_{Y\,water}^{-}$are exergy transformation for the water and CO_2 networks in the system. $\dot{E}_{y\,comb}^{+}$ is the exergy transformation of the oxidation network that can be approximated by:

$$\dot{E}_{y,comb}^{+} \cong \dot{M}_F\,EXV \tag{2}$$

$e_{d\,CO_2}$and $e_{d\,O_{2\,burner}}$ are the exergy of diffusion of CO_2 and O_2

For a generic fuel molecule $N_F\,C_aH_bO_cN_d$ oxidation with air corresponds to:

$$\frac{N_{CO_2}}{N_{Gc}} = \frac{a}{a+\frac{b}{2}+\frac{d}{2}+\left(a+\frac{b}{4}-\frac{c}{2}\right)(4.762\lambda-1)} = \tilde{c}_{CO_2}^{Gc} \tag{3}$$

For natural gas, assimilated to methane CH_4, and with an air factor $\lambda = 1$:

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$$\text{a=1,b=4,c=0,d=0 then:} \quad \tilde{c}_{CO_2}^{Gc} = \frac{1}{1+2+(1+1)(4.762-1)} = 0.095 \tag{4}$$

Hence the theoretical exergy required to separate 10% CO_2 from flue gas is:

$$\tilde{e}_{dCO_2} = 1\,\tilde{\boldsymbol{r}}T^0 ln\left(\frac{1}{\tilde{c}_{CO_2}^{Gc}}\right) = 5831.9\,\frac{kJ}{kmol_{CO_2}} \tag{5}$$

This is informative since the real benefit (product) of such a cogeneration system with CO_2 separation corresponds to the exergy of diffusion $e_{d\,CO_2}$:

$$e_{d\,CO_2} = \frac{\tilde{e}_{d\,CO2}}{\tilde{m}_{CO2}} = \frac{20107.5}{44} = 457\ {kJ}\Big/{kg_{CO_2}} \tag{6}$$

For comparison, (Clodic and Younes, 2002) mentions 1297, (Tuinier *et al*., 2011) 1800, tend to show that present capture efficiencies given in the literature are not very high. Since 1 kmol of CH_4 gives 1 kmol of CO_2, the exergy of diffusion of CO_2 corresponds to 1257 kJ/kgCH_4 that is 2.4% of the exergy value of the fuel CH_4. But considering the present efficiencies of capture these values are not negligible anymore.

Independently for the real capture efficiencies it is also interesting to note that capturing CO_2 from the atmosphere requires close to 3.5 times more exergy than from flue gas with 10% vol. of CO_2. In spite of that, CO_2 capture directly from the atmosphere is often promoted.

When it comes to the supply of O_2 for the burner, the lowest specific exergy needed corresponds to the exergy of diffusion $e_{d\,O_2\,burner}$.

For natural gas, assimilated to methane CH_4, two kilomoles of O_2 are required for a complete combustion (2 times 3946.5), that is 7893 kJ/kmol CH_4, to compare with the exergy value of 830174 kJ/kmolCH_4, that is about 1 %. This is again not a major part of the exergies considered but it is to be compared with the efficiency of separation of O_2 from the air of real processes. One way to analyse the supply of O_2 for the burner for practical consideration would be to introduce another exergy efficiency for systems that include both oxy-combustion and CO_2 separation as follows:

$$\eta' = \frac{\dot{E}_{GT}^{-}+\dot{E}_{SOFC}^{-}+\dot{E}_{Y\,CO_2}^{-}+\dot{E}_{Y\,water}^{-}-\dot{E}_{water\,pump}^{-}+\dot{M}_{CO_2}\,e_{d\,CO_2}}{\dot{E}_{y\,comb}^{+}+\dot{M}_{O_2}^{+}\,e_{d\,O_2\,burner}/\eta_{sep}} \tag{7}$$

In that way the efficiency of the cogeneration system is penalized to account for the processes upstream to make pure O_2 available. Note that a similar extension is not necessary in the numerical term related to exergy services provided with the capture of CO_2 since the exergy required is already accounted internally by the balance of the work terms.

An extensive review of most of the processes described above in connection to hybrid fuel cell-GT systems are reviewed in (He *et al*., 2023). They also provide a comparison between simulated values for different SOFC-GT concepts and the few experimental data available. Contrary to many other power technologies they do not identify a clear increase of electrical effectiveness of hybrid SOFC-GT systems with the power range of interest in this paper, that is a few kW to a few MW. However, they observe that experimental data on electrical effectiveness are around 10 to 15% lower than the simulated values.

4 EFFICIENCY OF HEATING AND COOLING SUPPLY TO A DISTRICT

The interest in coupling fifth generation DHC CO_2 network with advanced SOFC-GT is linked to the following synergies:

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a) Fifth generation DHC distribute heat at a temperature level that requires the use of heat pump in each building or group of buildings that are essentially electrically driven. The DHC network provides a low temperature sink all-year around for cooling flue gas from SOFC-GT, efficiently capture CO_2 from the H_2O-CO_2 stream of the anodic flow and improve the inversed Brayton cycle contribution.

b) Decentralized and pollution-free electricity generation for the need of the district including for the individual heat pumps can be done with CO_2 capture, the captured CO_2 being either compressed at the level of the DHC pressure (around 50 bars) and transported to a central collection plant or better transported at a lower pressure to the central collection plant via the annular inter-pipe space available when an external safety pipe is required. The collected CO_2 can then be purified and stored in liquid form for a summer use to generate synthetic natural gas by combining with H_2 from a district electrolyzer using excess solar electricity.

c) Potentially combined with the thermo-electric energy storage system based on transcritical CO_2 cycles as proposed in (Morandin *et al.,* 2013).

Obviously providing heat, cold and electricity can be done with various technologies but above all by technology combination. Exergy efficiency was shown in (Favrat *et al.,*2008) to rigorously rank the various technology options for heating and cooling. The present paper adds technologies with CO_2 separation and oxy-combustion systems. The proposed scheme based on a similar approach than in (Favrat *et al.,* 2008) relies in the decomposition of the system into eight subsystems including subsystems for energy transport and conditioning as shown in Figure 3.

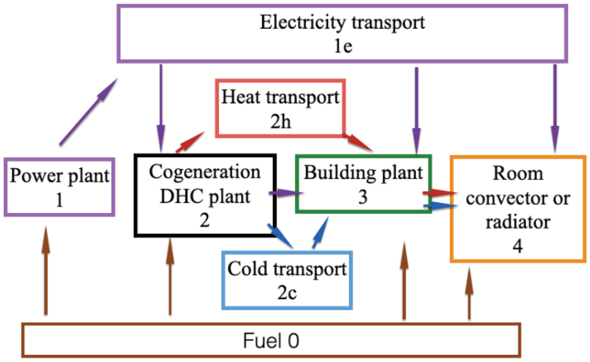

Figure 3: System decomposition for the exergy evaluation

As was shown in (Favrat *et al*., 2008) the ideal is to formulate the modeling in a way that the full system result is a multiplication of the exergy efficiency of each subsystem for the technology combination under consideration for the exergy ranking of options.

For the combination considered in this paper and supposing that the electricity produced corresponds to the electricity needs and for a winter sequence we have:

$$\eta_1\eta_2\eta_{2h}\eta_3\eta_4 = \eta \tag{8}$$

Comparing the different efficiencies for different generations of DH or DHC can be done on the basis of energy and exergy (Carnot) composites. Girardin *et al.* (2010) proposed to structure the heating and cooling data using composites like in Figure 4. While too often the energy needs of communities are only reported in terms of heat rates, energy composites allow to account for the temperature required by the heat distribution system inside the buildings. This parameter is vital to judge on the opportunities for heat pumps.

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Figure 5 shows the energy composites associated with the generations of DH or DHC for the average winter needs of Figure 4, but for one part of the city (1/10). If a Carnot factor is substituted to the temperature ordinates, the area underneath each composite represents the heat exergy to be considered and we talk about exergy (or Carnot) composites. The areas between each DH composite (hot composite) and the exergy composite of the heating needs (cold composite here represented as a black solid line) provides a graphical visualization of the exergy losses. The line with steps (a, b, c, d, d') is an approximate representation of the hot composite resulting from a fifth generation DH, since local heat pumps can adjust the condensing temperature to the actual needs of each building with small pinch difference. The demand 5a is from modern floor heating houses, 5b from retrofitted building, 5c older building, 5d and d' for the lower and upper part of hot water heating.

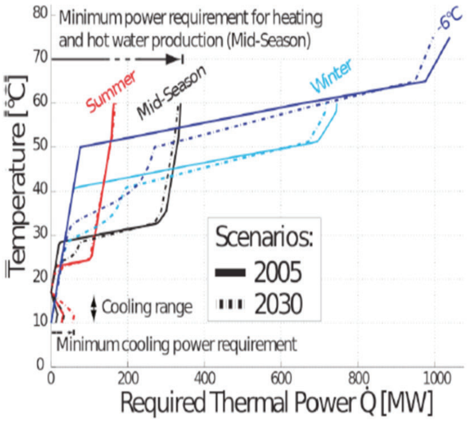

Figure 4: Energy composites for a city (Girardin et al., 2010)

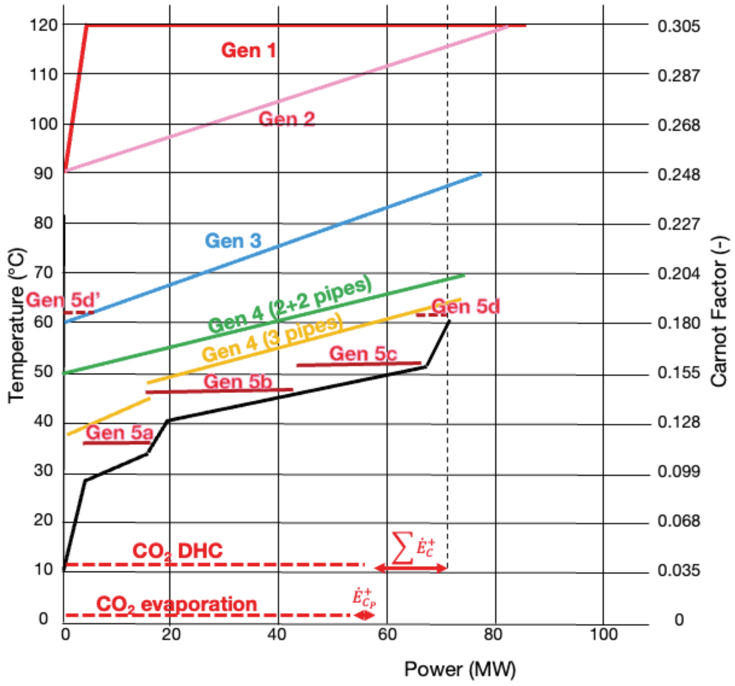

Figure 5: Energy composites (left scale) or Carnot composites (right scale) for the average case of winter of Girardin *et al.*, (2010) including the streams relative to the various generations of DH or DHC

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In this particular case, CO_2 liquid and vapor are distributed at 12°C, a temperature that is established from an open heat pump at the balancing central plant (2). At that plant in winter the incoming liquid is first expanded, evaporated and then compressed to be supplied to the vapor pipe of the DHC. This setup allows to adapt the evaporation temperature to the actual source temperature. In this case, lake water is considered for a heat source at 8°C and cooled down to 3°C with an evaporation of CO_2 at 1°C. $\dot{E}^{+}_{CP}$ is the power needed for the balancing plant compressor. $\sum \dot{E}^{+}_{C}$ is the sum of powers supplied to the building heat pumps along the network and CO_2 DHC indicates the sum of heat rates provided by the DHC to the building heat pumps.

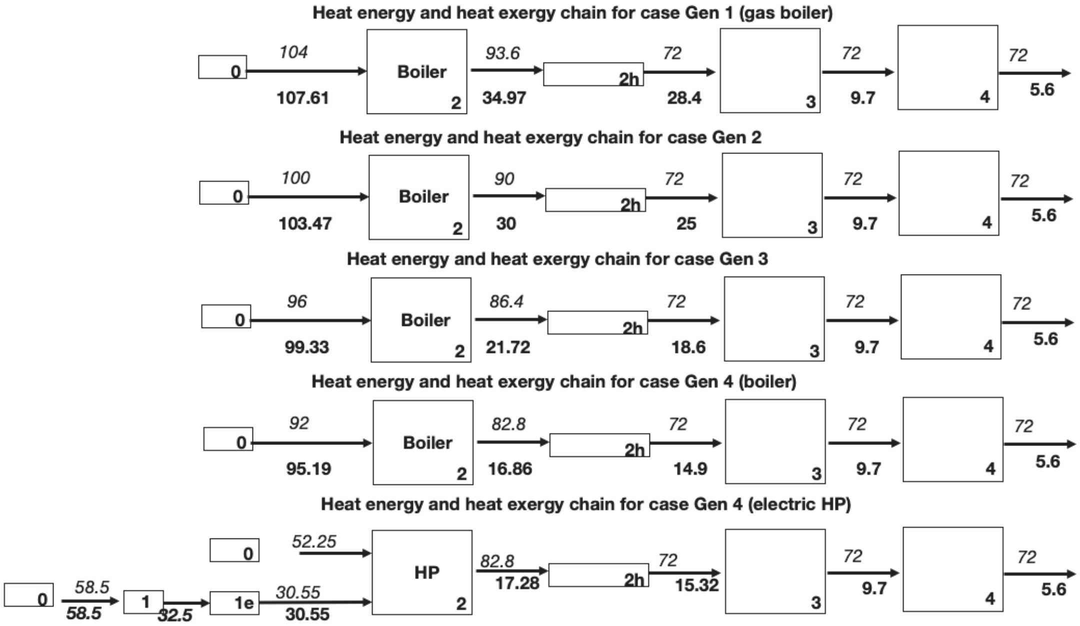

Figure 6: Block diagram examples of Generation 1 to 4 DH supplying the average winter needs corresponding to the composite of Figure 5

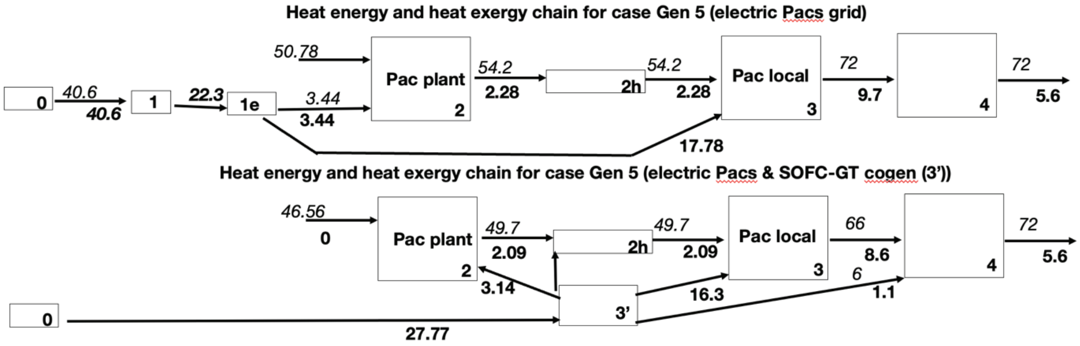

Figure 7: Block diagrams of Generation 5 DH supplying the same average winter needs

Figures 6 and 7 show the different energy and exergy paths to meet the average winter needs of the part of city considered in (Girardin *et al*., 2010). The first 4 are based on a gas boiler heat source. They differentiate by the levels of temperature distribution and the assumed energy losses that vary with the

DH supply temperature (30% for Gen 1, 25% for gen 2, 20% for Gen 3, 15% for Gen 4). No heat loss is considered for Gen 5 since the temperature distribution is close to the ground temperature. The boiler energy effectiveness is supposed to be 90%, the district heat pump exergy efficiency 55% and the local building heat pumps 45%. The electricity from the grid is assumed to have a 5% loss.

The last path given in Figure 7 introduces a cogeneration SOFC-GT unit along the DH with an electric efficiency of 71% and 21% of heat recovery at the same location. Table 1 provides the exergy efficiency of each technology used. For generations 1 to 4, the global exergy efficiency is the product of all exergy efficiencies along the path. For generation 5 this is not anymore possible since different parallel paths intervene.

The net result shows the interest of decreasing the FH supply temperature with exergy efficiencies that remain low when the supply is based on a fossil fuel boiler.

Gen 5 solutions dominate the other alternatives for heating, even without considering the heat recovery from other sources along the network like waste heat from data centers, office building air-conditioning, refrigeration and air-conditioning of shops and so on. Furthermore, direct free cooling would further improve those figures. Internal cogeneration with advanced SOFC-GT, dominates the alternatives considered and in combination with a CO_2 network allows to not only efficiently separate CO_2 but allows to collect it and transfer it to the balancing plants acting as collecting points.

Table 1: Exergy efficiency of different generations of DHC to meet the average winter demand of Figure 4

	η_1	η_{1e}	η_2	η_{2h}	$\eta_{3\prime}$	η_3	η_4	$\eta_{\square}$
Gen 1			0.325	0.813		0.341	0.577	0.052
Gen 2			0.290	0.833		0.388	0.578	0.054
Gen 3			0.219	0.857		0.521	0.578	0.056
Gen 4			0.177	0.885		0.650	0.578	0.059
Gen 4 HP	0.556	0.94	0.566	0.887		0.632	0.578	0.096
Gen 5	0.549	0.952	0.663	1		0.48	0.577	0.138
Gen 5 cogen	1	1	0.67	1.00	0.74	0.47	0.577	0.202

5 CONCLUSIONS

This paper shows the interest of coupling advanced fifth generation DHC based on CO_2 as heat transfer fluid with hybrid SOFC-GT cogeneration systems including CO_2 capture and/or oxy-combustion. The methodology to properly define the exergy efficiency in these systems is discussed. The interest of lowering district heating temperature is highlighted. Finally, a methodology is provided for ranking in terms of exergy efficiency all alternative technologies.

NOMENCLATURE

DH	District Heating
DHC	District Heating and Cooling
SOFC-GT	Solid Oxid Fuel Cell - Gas Turbine
GIS	Geographic Information System
GHG	Greenhouse Gas
IEA	International Energy Agency
CCS	Carbon Capture and Storage
SNG	Synthetic Natural Gas
η	Exergy Efficiency
e_d	Specific exergy of diffusion

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$\tilde{c}$ Molar Fraction
$\dot{E}$ Exergy

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