Energy efficiency is key for more sustainable energy systems and cities

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, energy efficiency is key to achieve this goal with a relative contribution 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. The nuclear case is perhaps the most striking one, since some fourth generation concepts like the molten salt reactors could generate up to 50 times more electricity per kg of uranium compared to Second or Third generation reactors (Tani, Haldi, Favrat; ECOS 2010). This is linked to a better use of nuclear fuels with at the same time a limitation of the production of very long-life wastes. However economic aspects have so far prevented their development, even if new projects emerge along this path. As far as road transportation is concerned, operational efficiency gains of the order of a factor 3 can be achieved with the transition to electrical vehicles, thanks, in particular, to braking energy recovery, better batteries and more efficient motors. In the domain of domestic heating, substitution of direct electric heating systems by heat pump allows an efficiency improvement by a factor 3 to 5 depending on the heat source and the heat convectors used. Replacing fuel boilers by a combination of heat pumps and cogeneration units, not necessarily at the same location, can offer efficiency improvements by a factor 2 to 3. Decentralized power technologies also have a significant margin for efficiency improvement. Besides the discussion of performance indicators, this contribution intends to focus on two innovative technologies, which separately or combined, have a great potential to contribute to more sustainable communities and cities.

Present cities are wasteful in particular due to the lack of synergies between users. Heating and hot water services are still predominantly provided by simple boilers whose fumes laden with pollutants are locally evacuated through chimneys. At the same time, waste heat from cold users (office building, shops, supermarket, servers) in the same area is directly dumped into the atmosphere. On the global level, climate change increases the number of weeks per year with high temperatures in many parts of the world where air-conditioning was not a major concern. Hence the need for planners to not only think about infrastructure for heating but also for heating and cooling in a way that does not increase heat islands in cities. In terms of efficiency most cities offer a contrasted picture with a mix of retrofitted buildings with up-to-date insulation and lower heating temperature needs and non-retrofitted buildings with higher heating temperature needs. Therefore, the previous generation of District energy networks with a high supply temperature to meet all the various heating requirements, or District cold networks with excessively low temperature for air-conditioning purposes, must be called into question.

Emerging low temperature (5 to 15°C) district heating and cooling (DHC) of 5th generation, sometimes referred to as "anergy" networks, can substantially improve the synergies between users by providing heat to local heating heat pumps and direct cooling to most cold users, while providing a way to recover the waste heat from heat emitters and avoiding the dissemination of cooling towers. Of course, a balancing plant needs to be implemented at the district level with a central heat pump and/or a cogeneration unit to compensate for the unbalance between the needs of the various users. Heat or cold sources for the balancing plants can be based on ambient heat: treated water from sewage water treatment plants, lakes or rivers, fields of shallow geothermal probes under parks, or centralized cooling towers. Two types of 5th generation DHC are currently offered. Water networks with small differences of temperature requiring large piping systems, or networks using CO_2 in closed loops as a transport fluid with more compact pipes requiring less digging of the streets and less embedded energy. In the latter case the CO_2 network with one vapor pipe and one liquid pipe at about the same temperature and pressure acts like an umbilical cord through the district and primarily plays on the latent heat of this inert natural refrigerant. Such a network was put into operation in the Swiss city of Sion (ExerGo.com). Although performance results are not yet available, a theoretical study with such a system in a district of Geneva showed that more than 80% of the energy required can be saved compared to the existing boilers and standard cooling units (Henchoz, Weber, Marechal, Favrat; Energy 2015). However, the new approach implies a slight increase in the district electricity consumption, hence the interest to integrate cogeneration.

Solid Oxid Fuel Cells (SOFC) that operate at high temperature are particularly efficient for decentralized electricity production or cogeneration of heat and power without local pollutants emissions. They can directly convert most methane (CH_4) from natural gas (NG) and have the intrinsic interest of separating O_2 from the other components of air, mainly N_2. Air is typically introduced at the cathodic side, and partly reformed NG at the anodic side. At the operating temperature (about 800°C) the oxygen selectively crosses the membrane from the cathodic to the anodic side and oxidise some 80 to 90% of the fuel. The remaining inoxidized gas needs to go through a post combustion step, ideally with an oxidizer without nitrogen (ex: O_2). The anodic outgoing flow is then essentially made of CO_2 and H_2O. The lower the cooling temperature of the flue gas, the better the H_2O can be condensed and the CO_2 separated. Hence the interest in combining CO_2 networks with SOFC cogeneration units at the district level, providing access to a low temperature all year around and a way to potentially transport the separated CO_2 via a separate low pressure pipe to various collection points throughout the city. One further efficiency improvement can be achieved by combining the SOFC with a gas turbine cycle (GT or Brayton) making a so-called hybrid SOFC-GT cogeneration unit. Since most practical SOFCs are planar rather than cylindrical, atmospheric pressure is preferred in the cells. One patented hybrid concept introduces a sub-atmospheric Brayton cycle. The whole anodic flow from the post combustion is expanded in a turbine down to a pressure of the order of 0.3 bars abs., the water vapor is condensed and pumped separately to the atmospheric pressure, and only the CO_2 needs to be compressed in a compressor to the original atmospheric pressure. Extra power can thus be recovered topping the electricity production of the SOFC. Overall electrical effectiveness of more than 69% (based on the fuel lower heating value) and exergy efficiency of more than 70% can be theoretically achieved, with even 7 to 8 extra percentage points with more advanced configurations based on the same process (Facchinetti, Favrat, Marechal; Fuel cells 2014). This is of course valid for both NG and synthetic natural gas (SNG). Even more promising is the same concept applied to hydrothermally gasified waste biomass, as the captured CO_2 would allow a net removal of CO_2 from the atmosphere (Facchinetti, Gassner, d'Amelio, Marechal, Favrat; Energy 2012). Electrical effectiveness of 63% could be achieved when these two technologies are integrated at the same location, meaning an improvement of some 4% compared to situations where the two technologies are applied on different sites and therefore not integrated. While there is a lot of discussion about dismantling natural gas city networks in the context of zero carbon societies, their renewed use to distribute more and more SNG to feed efficient cogeneration units with CO_2 separation should be seriously considered.

Flexibility is also important in the domain of energy systems, and from this point of view SOFC have an additional advantage, which is that the flows can be reversed. They can operate as high-temperature electrolysers (SOEC) when an oversupply of electricity is available from the grid and generate hydrogen for other uses including energy storage, feeding hydrogen vehicles, supplying methanation plants or simply feeding the post combustor of the hybrid SOFC-GT plant at high electricity or heating demands.

Thanks to the emerging use of high-pressure composite pipes from the offshore gas industry, CO_2 based DHCs are well on their way, both economically and energetically, to compete with other DHC systems. The issue is more difficult for SOFC units that still suffer from high specific costs due in part to low production levels and to lifespan issues due to potential deposits on, or structural transformation of, the cathodes and anodes. Significant progress is being made on these two fronts and we can expect major advances in the years to come. What is particularly nice with that technology is that, contrary to low temperature fuel cells, it does not rely on expensive catalysts or require drastic purity of hydrogen feed.

We cannot refer to energy efficiency without having the appropriate tools to measure it. Unfortunately, in practice, still rudimentary indicators based only on the First Law of thermodynamics are being used today. Since the First Law states that energy is being conserved most of the time the performance values obtained are mainly measuring the degree of thermal insulation of the energy system considered and not its ability to provide useful energy services. Energy in Greek was etymologically supposed to characterize the capacity to do work and not to designate a value that is conserved. More rigorously, the capacity to do work is expressed by the notion of exergy, a notion that combined First and Second Laws of thermodynamics. An illustrative example of the difference between these two notions is the fact that the First Law "efficiency" of home boilers is quoted in the commercial literature with values between 70 and 105%, while their exergy efficiency is indeed only of 3 to 10% depending on the temperature of the heat delivered and on the atmospheric temperature. Higher than 100% values in First Law "efficiencies" result from the different choices of the fuel heating values taken as reference. Such inconsistency does not exist for exergy efficiencies (Borel, Favrat; EPFL Press 2010). A proposal to include the exergy efficiency rather than the so-called energy "efficiency" as the performance indicator for the active part of energy systems in communities was translated into a local Law on energy (Favrat, Marechal, Epelly; Energy 2008). The proper way to analyse the different options to heat or cool buildings is summarized, with a decomposition in 4 subsystems going from a power plant typically outside town, a DHC plant, a building plant and room convectors. The individual exergy efficiency associated with the available technologies for each subsystem can be documented in structured lists and the overall efficiency calculated as a product of the efficiencies of each subsystem. One of the important conclusions is the following: "Supply heat at the lowest temperature as possible and supply cold at the highest temperature as possible". Early results penalized DH systems due to the assumption made of the need to supply heat at 80°C. The application of the two technologies described above (Fifth generation CO_2 networks and SOFC-GT) significantly improve the ranking of these DH systems in the list of best solutions.

Another important methodological approach is to have an appropriate documentation in particular of the demands for heating and cooling. Geographical Information Systems (GIS) should not only include the amount of energy needed but also the temperature level required, since this information plays a major role when dimensioning heat pumps systems (Girardin, Marechal, Dubuis, Calame, Favrat; Energy 2008). Developing more sustainable systems implies a paradigm shift in comfort energy and power supply. For heating, the idea is not to start a high flame temperature and then downgrade it to satisfy the different services, but to start from the ambient temperature upwards to satisfy the same services. For power supply, the idea is not anymore to rely solely on a centralized power grid but to also consider decentralized cogeneration solutions with their increasing efficiency to complement the supply from other local renewables.