Hybrid Cogeneration of Heat and Power using Concentrated Solar Power and Gaz with direct use of the heat in food processing industries

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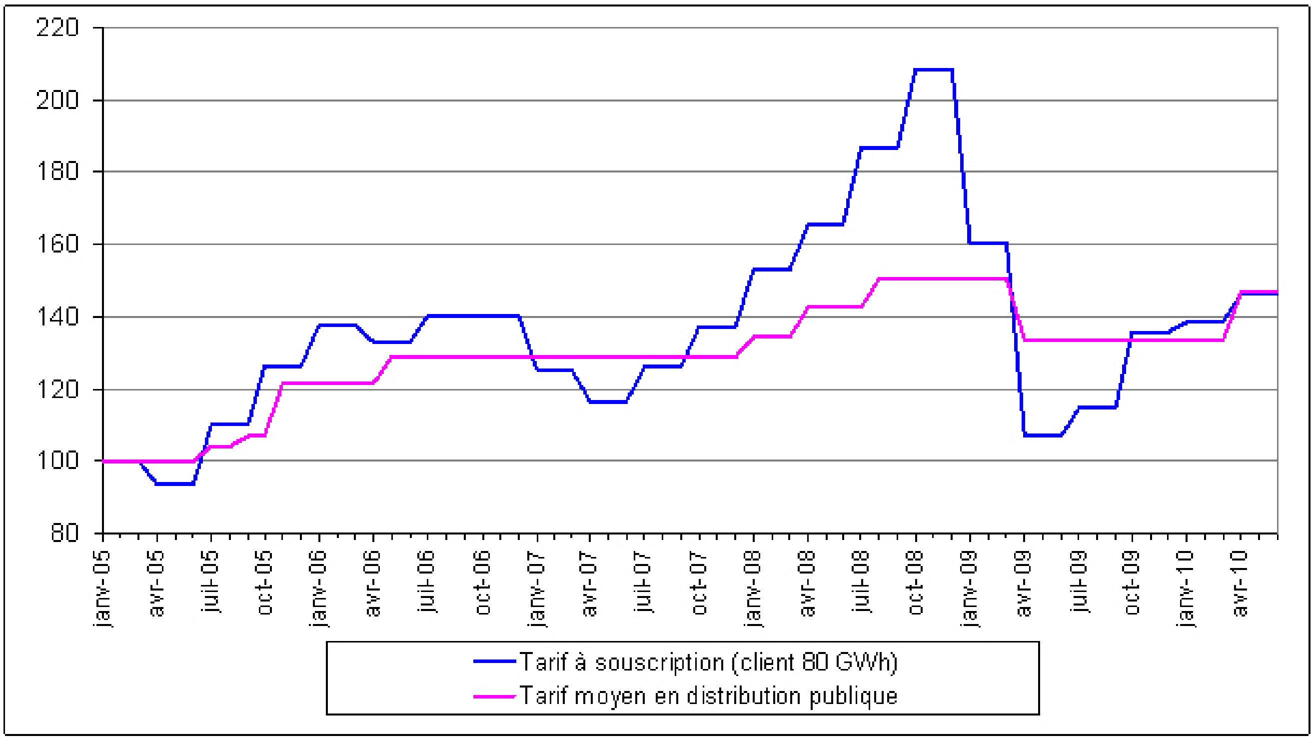
Introduction

Many food processing industries make heavy use of heat at temperatures from 80 to 200 degrees centigrades : steam generation, cooking, blanching. In Europe, this heat is mostly produced from natural gas, whose price rose from 45% in France between January 2005 and April 2010. [1]



Evolution of the gas prices in France between 2005 and 2010
(100=reference price at the beginning of the period)

So far, in plants of industrial size, the heat is almost always produced using gas or even worse, electricity. Using solar energy for heat production in this range of temperatures has been so far limited - because concentrating the radiation is usually required - mostly to a very few small-scale hand-made installations (the Scheffler reflector) in remote areas where other sources of energy are unavailable, unreliable or expensive due to geographical isolation.

Example of a Scheffler reflector,
built for experimentation and training

The project is to study what appears a probably technically feasible and economically profitable option to use solar energy in these processes.

Abbreviations

FPI = food processing industries

CSP = Concentrated Solar Power

HTF = heat transfer fluid

WF = working fluid (in thermodynamic cycles)

HG = heat generation

PG = power generation (electricity production)

SP = steam production

FIT = feed-in-tarifs (for electricity production and injection into the electric grid)

W_r = Watt (solar radiation)

W_{th} = Watt (thermal)

W_e = Watt (electrical)

Description of the base idea

Solar cogeneration

Cogeneration of heat and power is a well-known principle based on the fact that when it is possible to use both the heat and the mechanical power produced by a fuel-powered engine (typically a gas turbine or 4-strokes motor), the overall efficiency (heat plus mechanical power) is higher than the ones achievable producing only heat or only mechanical power.

Applying the principle of cogeneration to solar power has been so far rare and normally restricted to photovoltaic systems (PV), using the residual heat extracted by a cooling system (either water or air). However with these systems one may only achieve low temperatures heat (40 to 60ºC), as temperature degrades significantly the performance of PV cells (from -2 to -5% per 10K) and potentially damages them either quickly or over the long term.

The main issue of cogeneration is to have a possible use for the generated heat. Obviously the higher the temperature of the heat source, the more numerous are the possible uses. For this reason, cogeneration using PV-cells as the heat source is limited in its range of applications.

CSP

Concentrated Solar Power systems (CSP) are almost systematically used for electricity production (PG) usually using steam turbines in various thermodynamic cycles (for example : a Rankine cycle or an organic Rankine cycle). There are a few examples of CSP systems using the produced heat for thermal uses instead but they are relatively uncommon.

CSP systems work in the range of much higher temperatures for their working fluids (WF), always above 100ºC and often above 300ºC [5]. Compared to the case of PV-cells, increasing the temperature has the opposite effect : it increases the efficiency in electricity production [3].

The difficulty in using the heat of CSP, as mentioned above, is finding an application with a need for heat matching the possible production CSP system, which, unlike fuel powered engines, depends on the sun, in particular, the daily and seasonal curves of the production. Although heat storage is a possibility, it adds costs and it is better to consider only short-term storage, used for output smoothing over periods of a few days maximum.

Except for those using Stirling or Ericsson engines, most CSP systems are based on generating steam to power a turbine. They achieve this, either by direct steam generation (the WF and the HTF are the same) or by using separate WF and HTF.

Food processing industries

Food processing industries offer a very good match for being a heat consumer :

- They use a lot of heat in the range from 80 to 150ºC. [6]
- They actually often use this heat for steam production, so the steam used for PG in the turbine can be used directly, given it has enough residual energy (enthalpy).

- The production calendar of these industries is connected to the agriculture, and therefore grossly to the presence of the sun.

Hybridisation

Implementing a cogeneration of heat and power on a CSP system would already be a step in innovation in itself. This has already been the case of research but gave birth to almost no industrial applications.

However, such system would interest few people : as all systems powered only by solar energy, it would have the drawback of depending completely on the sun and not enabling sufficient production at certain times.

This may be acceptable for a business whose sole purpose is power generation to sell it to a client ready to take the generated power any time of the day (i.e.: solar-generated electricity fed into the grid). But it is not acceptable for a business, generating power heat for its own consumption and who wants the energy available when it needs it.

There are two answers to this problem : storage and hybridisation [4].

Cogeneration was a solution initially developed and nowadays well mastered with fuel-powered systems. In the other hand, storage in CSP systems is still subject to a lot of R&D when temperatures above 150°C are considered.

Hybridisation offers the possibility to retrofit cogeneration systems in place around the world and to be incorporated to existing products - although the development of specific equipments would make more sense on the long term (such as low enthalpy turbines).

Thus, choosing hybridisation makes more sense. Still, storage may be to a lesser extend a component of the investigated designs as it enables smoother operations.

Another advantage of hybridisation compared to non-hybrid CSP plants is that it enables running the turbines close to their design point. This point is worth further investigation.

State of the art

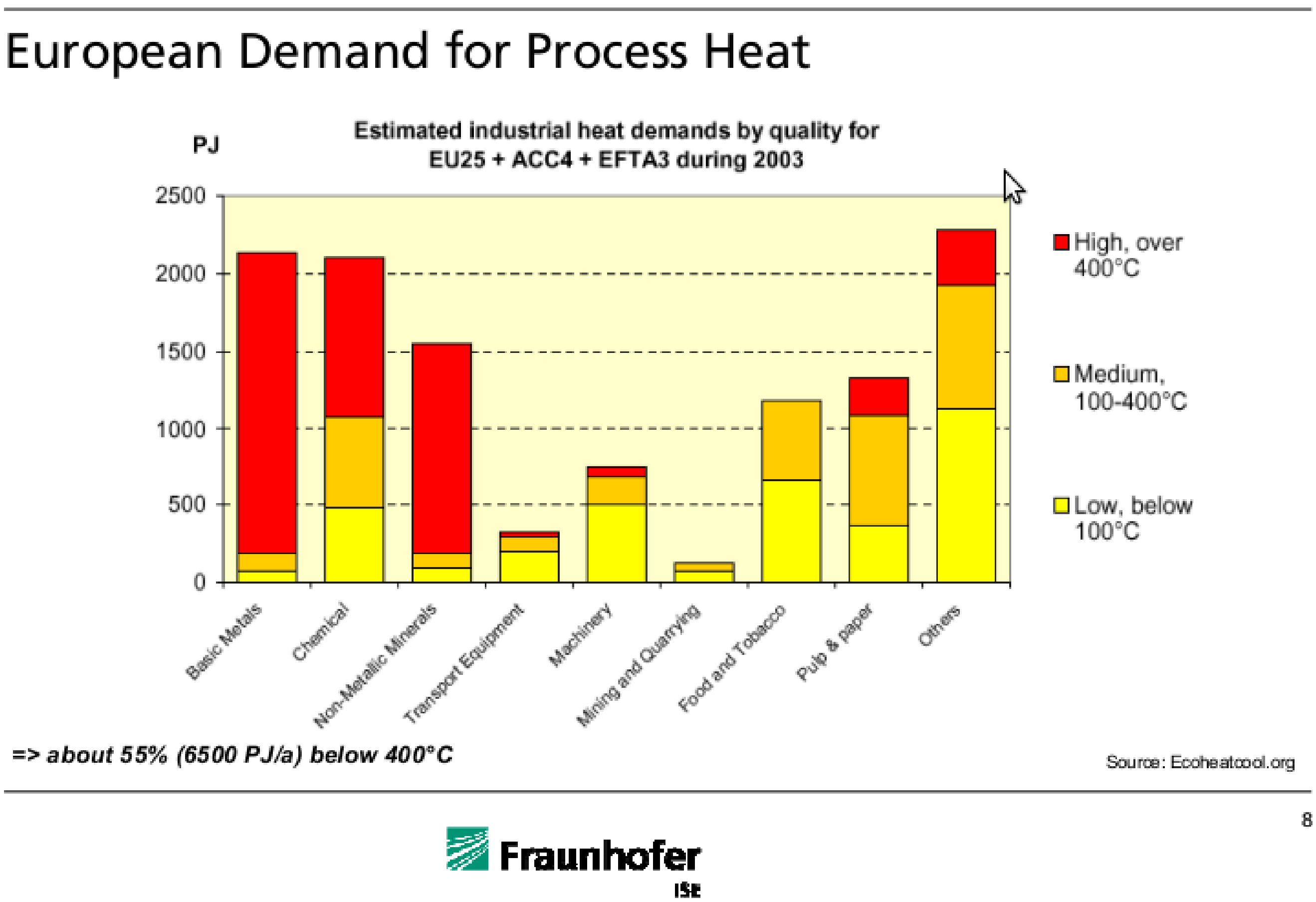
- CSP is booming now, but almost almost all applications are focused on the highest end of the power range (at least 5 MW_e) [2], which has put CSP so far in the category of centralized power generation systems. This is due to the fact that the efficiency of CSP power plants tends to improve with its size [3]. However, matching the size of a plant to the possible use of heat by a local industrial plant should bring a higher global efficiency (heat + electricity).
- There are a few institutions working on the topic of CSP for heat production, but they are mostly focused on using heat in buildings with the heat source used in cooling absorption cycles. These systems have a potential huge market (all the gigantic buildings of the South Emirates, to start with), but producing cold out of heat through absorption cycles is a technologically more complicated and expensive process than using the heat directly.
- Using the heat of a solar system requires an application whose demand curve matches the

radiation curve of the sun.

- Many FPI have now cogeneration units wherever they have a huge production plant and they can sell their surplus electricity production for a profit.

Advantages of FPI for solar generated heat

- Matching of the demand curve with the energy production curve, in seasonality and potentially daily with adjustments.
- Possibility of using residual heat directly on-site, leading to higher global efficiency of the use of solar power.
- Production plants are most often located close to the production, in rural areas, where flat open lands can be found, and hopefully sunny weather.



Estimated demand of process heat in Europe. As it can be seen, the food industry has a notable share (over 1000 PJ = 280 000 Gwh) and uses medium or low temperatures.

Legal framework

- Although most of the European countries now have FIT for solar produced electricity and production of electricity by firing cogeneration units out of fossil fuels or biogas, there is no existing legal framework for solar cogeneration. This is actually an evidence that such idea is still novel.
- Although one might hope to benefit from a FIT with bonuses for both the use of solar energy and cogeneration, it is likely that the solution to be implemented by governments by a new FIT. It would legitimate to calculate basing oneself on the saving of fossil fuel compared to the baseline of such cases (using gas separately for HG and PG), mimicking the Clean Development Mechanism of the Kyoto Protocol. In any case, one may expect a high FIT, as currently existing FIT often apply to all solar-generated electricity.

Project proposal

The project is to investigate the technical feasibility and the economical profitability of cogeneration of heat and power in food industries using a hybrid system of concentrated solar energy and fuel-powered system.

The milestones would be :

- In-depth investigation of heat demand and use in the processes of FPI, leading to the creation of numerical models.
- Scientific review of existing systems (CSP and fuel-powered cogeneration). First choice of design options based on obvious conclusions not requiring numerical simulation.
- Numeric modelling of the selected possible designs and simulation of operation facing the models of demand created during the first milestone.
- Choice of a design (which will certainly depend on the case study used to establish the models of heat demand) and optimisation of the system through simulation.
- Building of a small-scale prototype (3-15 kW). Testing and comparison with the numerical model. Improvement of the model to match the actual test results.
- Study of economical profitability based on the experience gained through prototyping and numerical modelling.

If the project is successful and shows that this type of system would gain economic profitability, the next milestone toward the full development of the technology would be building a medium-scale prototype (about 100 kW) directly in the production site of FPI, monitor and optimise it.

Examples of options to be studied

This section gives a non-exhaustive list of examples of configuration variants that would be to be studied in the first milestones of the project, during the selection process.

The reader will see that the same variants appears several times in the next paragraphs. This is because each one of them actually reflect different ways of classifying the systems.

Possible optical concentrators

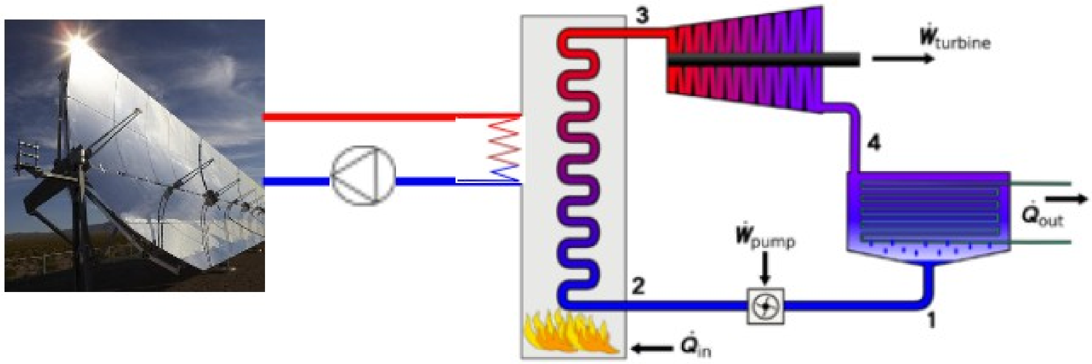
- Parabolic dish : probably not suitable for this type of use (due to the movable focus point).
- Scheffler reflector (parabolic with a fixed focal point) : only for small-scale applications (under 10 kW_r), as its scalability is limited.
- Parabolic trough and Fresnel : the scalability of theses systems, as well as the fact they might be located on top of industrial buildings, seem promising.
- Central receiver : the high concentration ratios offered by these systems are probably unnecessary.

Possible hybridisation variants

- The PG stages are separated but the HG stages is common to both solar and the fuel-powered components.

  Example : the CSP part of the system is a closed thermodynamic cycle with its own steam turbine for PG but the stage of HG (coming from the condensation stage of the thermodynamic cycle) is common with that of a gas turbine, which also has a separate PG stage.
- The stages of both PG and HG are common to both components.

  Example : the solar heat is used as energy input in the open thermodynamic cycle of the fuel-powered cogeneration unit (by heating the air and the methane flowing into a gas turbine, for example [7]).



hybrid Rankine cycle (steam turbine) with two heat sources : a burner and solar energy

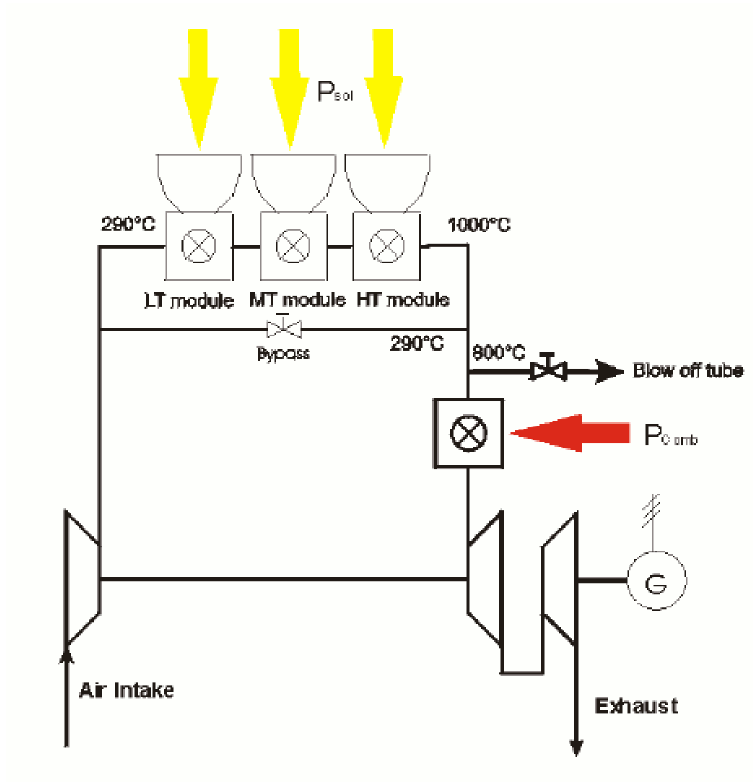


Fig. 3: Scheme of the SOLGATE test system

The Solgate project : use of CSP in a Brayton cycle (gas turbine).

- The PG from solar energy is separate and its HG is used to boost the fuel-powered component.

  Example : the CSP component is a closed thermodynamic cycle with its own steam turbine for PG, but the heat (from the condensation stage) is used to warm up the gases flowing into a gas turbine, similarly to the previous example, except that much less heat is brought in.

Possible points of application of the solar heat

- To the water being boiled for steam generation.
- To the gases entering the boiler / turbine (air a/o fuel).
- To the gases in the turbine after compression but before burning.
- To the generated steam (for over-heated steam).

Possible cogeneration systems to retrofit

Technology used for power generation	Variants and explanations
none	• Using the solar heat for steam generation, in combination with a boiler (not a cogeneration but simply a hybridisation of the steam production).
Steam turbine	• Using the solar heat for steam generation, with a steam turbine positioned in the steam flow to produce electricity.
Gas turbine	• Using the solar heat to warm up the water at the steam generation stage of a cogeneration gas turbine (i.e. : the solar heat is being injected after the electricity generation stage but before the steam generation stage). • Using the solar heat to warm up the air flow entering the gas turbine, before steam generation and electricity production stages. • Using the solar heat to warm up the air flow in the gas turbine after compression, but before burning the gas.
Combined cycle (gas turbine + steam turbine)	• Using the solar heat in a combined cycled is feasible and would probably lead to interestingly high efficiencies. However the rated power of this type of installations (hundreds of MW) is higher than what is typical for cogeneration plants and probably not relevant for a FPI.

Required temperature variants

The heat production could also be based on the condensation stage of the used thermodynamic cycle. The need to achieve temperatures higher than 80 degrees centigrade makes attractive cycles working at pressures higher than the ambient one (ex : the PWG cycle , often used in geothermal energy).

Possible variants in using the heat

- Direct steam generation in open cycle.
- Heating a HTF (in closed cycle, then) used for cooking with no steam generation.

This choice will be connected to the type of cooking process in use (blanching, steam cooking, …). The production constraints may make more attractive a versatile system capable of both variants.

Heat storage variants

- No storage.
- Short-term buffering, up to a few minutes of production, using masses with thermal inertia.
  This would enable smoother operations, but also would enable avoiding loosing production at the stage where the heat is being used.
  Indeed, the food transformation processes may work in batches, semi-continuous or continuous flows (depending on the size of the plant, usually), and small pauses in the heat demand may occur during operation.
- Traditional intra-day heat storage.
  This solution is likely to be too expensive and not required since the systems are already meant to be hybrid and being able to use a fossil fuel when sun is not available.

An economical analysis is necessary to find the optimum.

Conclusion

As the reader can see by itself, there are many ways of putting together CSP and a fuel-powered cogeneration system. The optimal choice will surely depend on the economical value given respectively to heat and electricity. Studying all the possible variants and choosing the one(s) subject to further modelling and study will be an important milestone.

References and annexes

- [1] Report of the French national regulating commission of energy (*Commission de Régulation de l'Énergie*) : http://www.cre.fr/fr/marches/marche_du_gaz_naturel/marche_de_detail
- [2] No commercial small or medium-scale applications exist, among other reason because of lack of commercial interest. See STG international (http://www.stginternational.com/) for a non-profit but commercial attempt of making small-scale CSP profitable in a niche market (although I doubt it be viable).
- [3] The Carnot cycle efficiency increases as when the temperature of the hot source increases. However, radiative losses increase exponentially and there is in fact an optimum temperature for the overall efficiency.
- [4] One can distinguish different degrees of hybridisation of a system :
  - *Alternate* : the system can use different energy sources but only one at once.
    Example : a fuel burner capable of using methane or propane but where you have to change the hose.
  - *Complementary* : the system can use different energy sources at the same time, but each one of them uses different appliances to transform the energy into the desired form.
    Example : having two burners using different fuels chained in series onto the same water line.
  - *Merged* : the system can use different energy sources at the same time and in the same appliances.
    Example : co-firing of wood and coal in the same burner.
- [5] Example : in the case of a CSP plant using direct steam generation, the steam enters the field at 120ºC and 75 bars (extracted from the thesis *ANÁLISIS Y PROPUESTAS DE SISTEMAS SOLARES DE ALTA EXERGÍA QUE EMPLEAN AGUA COMO FLUIDO CALORÍFERO* of María José Montes Pita at the *Universidad Politécnica de Madrid* in 2008, p.89).
- [6] from a discussion with the engineering office of one of France's main food processing company, they produce steam at 10 bars and use heat at 120ºC or 90ºC.
- [7] as proven feasible by the project Solgate (solar hybrid gas turbine electric power system, a project partly funded by the European Community in the framework of the 5th RTD Framework programme, 1998-2002) and the Aora small power plant in Israel.

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