Energy for Sustainability 2013
Sustainable Cities: Designing for People and the Planet
Coimbra, 8 to 10 September 2013

MISSING THE "SPARK GAP": FEASIBILITY STUDY FOR A TRIGENERATION SYSTEM IN A FISH FREEZING INDUSTRY IN PORTUGAL

Vitor Ferreira, José Ribeiro, Adélio Gaspar, José Costa, Avelino Oliveira

ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra
Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
Email: vitorferreira@adai.pt, web : http://www.adai.pt
jose.baranda@dem.uc.pt, web: http://www.uc.pt/fctuc/dem/
adelio.gaspar@dem.uc.pt
jose.costa@dem.uc.pt
avfmo@isec.pt, web: http://www.isec.pt

Keywords: Agro-Food Industry; Freeze-storage; Absorption refrigeration; Trigeneration

Abstract *The Project "Inovenergy – energy efficiency in the Agrofood industrial sector" consists of the characterization, auditing and simulation studies with the main goal of providing specific energy efficiency measures that might help small-to-medium enterprises (SME's) cut their energy costs.*

As part of the study for Best Available Practices and Technologies (BAPT), this short paper describes the feasibility study for a trigeneration system capable of producing cold at about $-33^{o}C$ *in a fish freezing plant, aiming to replace the base-load vapour compression chiller that is responsible for about 65% of the plant's annual energy requirements. A brief introduction to thermally activated technologies is presented focussing on classic vapour compression and the ammonia absorption cycle which is currently the only marketed technology capable of reaching freezing temperatures. Considerations are made regarding the required electricity to heat cost of the two cycles and it is found that the required "spark gap" must be under 2.5. For the study-case of a state-of-the-art fish freezing industry, it is concluded that this technology is not able to compete with the traditional ammonia compression system.*

1. INTRODUCTION

The Agrofood industry represents about 14% of the manufacturing industries in Portugal [1]. Among these, over 99.3% are micro and SME (Small and Medium Enterprises). Often, these industries present annual energy consumptions under 500 tons of oil equivalent (toe), exempting them from mandatory energy audits. IDAE [2] reports that the Food sector in Spain, although being the 5th most energy consuming, has the highest energy savings potential. In Portugal, no such studies were made to date, but it is conceivable that similar conclusions will be presented through the results of Project Inovenergy.

Due to the steady increase in electricity costs and a growing concern about energy efficiency, trigeneration systems are gaining relevance as a way to cut costs and save primary energy [3-5]. This paper addresses the state-of-the-art of a thermally activated refrigeration system capable of achieving freezing temperatures of -30ºC and below. A study-case is presented to assess how this alternative stacks up against a state-of-the-art electrically driven refrigeration that provides the base-load chill to a set of storage chambers with fish products.

2. BRIEF REVIEW OF THERMALLY ACTIVATED TECHNOLOGIES

Much has been written regarding thermally activated technologies for refrigeration and freezing purposes [6]. This review is focused on NH_3-H_2O absorption chillers (AC), the only technology commercially available that is able to achieve the required purpose.

2.1 Basic principle of the absorption cycle

The absorption cycle in its simplest form is very similar to the compression cycle (CC). They both present an evaporator, a condenser and an expansion valve. The main difference lies on the compressor of the CC: electricity has to be fed to compress the refrigerant gas so that heat can be transferred from the space/process to be cooled to the heat sink. In the AC, the pressure/temperature is increased by heating it directly so that the refrigerant, which is part of a binary mixture with different boiling points, is separated (boiled) from this solution. This happens in the generator (a heat exchanger). At the generator's exit, the cycle undergoes the same steps as the CC. After the evaporator the refrigerant goes into another heat exchanger – absorber, where it is mixed and re-liquefied in the binary mixture. This liquid solution is then pumped back to the generator, where heat (and consequently pressure) is provided, thus restarting the cycle.

3. CASE STUDY: BENCHMARK AND CURRENT ENERGY REQUIREMENTS

The company with the lowest specific energy consumption (kWh/kg) is the plant chosen for this study (blue bars – Fish_1 on Figure 1). A feasibility assessment of replacing a conventional (compression) chiller acting as the base-load by a waste-heat driven technology (absorption chiller) was the main goal. This plant was chosen to compare these different technologies because it is a relatively new plant, using state-of-the-art refrigeration technology. In the right axis of Figure 1, the relation between stored tonnage and refrigerated volume is depicted by the red line. This further supports the decision to study these competing technologies at this particular plant – Fish_1.

Figure 2 shows that this industrial unit presents quite regular energy requirements throughout the year with a slight increase in the months of the second semester. Regarding the demand charge diagram, it is seen that for most of the 24 day period the base-load requires about 150 kW (red line in Figure 3). The peaks of about 350 kW are related with fish processing. Based on the chiller's (and auxiliary equipments) average energy consumption, an impact on annual energy bill of about 65% (assuming 95% annual availability) is found. Being responsible for such an energy share and due to its consistency in terms of energy input, an alternative trigeneration sized specifically to match this chiller cold output was studied.

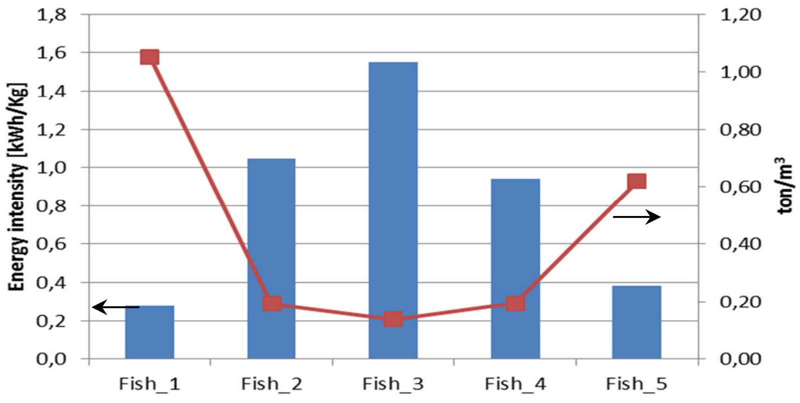

Figure 1: Energy intensity and specific storage (per refrigerated volume).

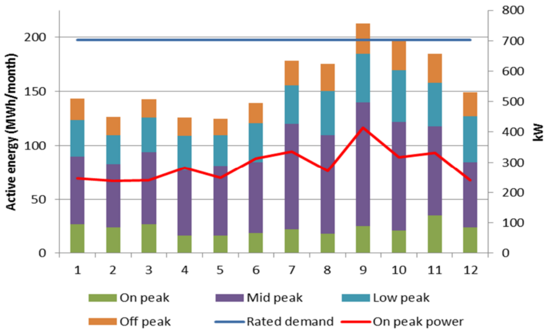

Figure 2 – Monthly energy consumption

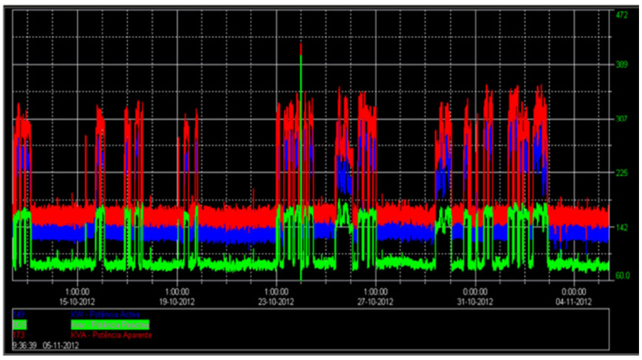

Figure 3 – Refrigeration demand in a 24 day period

Based on the AC's Coefficient of Performance (COP) at the desired temperature and required heat input, three alternative configurations for the trigeneration were studied: i) a set of 3 gas microturbines, a technology that has the advantage of system simplicity as the flue gas could be directly used into the AC; ii) two microturbines and a post-combustion, where the high O_2 content in the microturbine's flue gas could be directly used as combustion air to the auxiliary burner; iii) an internal combustion engine (ICE) was reviewed in light of the higher electrical efficiency. To assess the systems' economics the following evaluations were made:

$$Trigen_{\,operating\ cost}[€] = gas\ input \times annual\ operating\ hours \times gas\ price \quad (1)$$

$$Trigen_{\,annual\ savings}[€] = Electr.avoided\ purchase + Electr.sold\ to\ grid \quad (2)$$

The second term in eq. (2) is a function of the produced electricity minus the electricity required "in-house" in the trigeneration scheme (i.e., without the contribution of the base-load chiller). Consequently, eq. (2) becomes:

$$Trigen_{\,annual\ savings}[€] = Electr.avoided\ purchase + \big[Electr.produced - Electr.required_{Pre-trigen} - Electr.required_{base-load\ chiller}\,\big] \times Sale\ price\ to\ grid(3)$$

The assumed prices of natural gas and of purchased and sold electricity are listed in Table 1.

Nat. gas: 46 €/MWh	Purchased electricity$^{(1)}$: 109.56 €/MWh
Sold electricity at fixed rate$^{(2)}$: 99.23 €/MWh	Sold electricity at bi-rate$^{(2)}$: On-peak: 108.35 €/MWh; Off-peak: 87.37 €/MWh

(1) Weighted average of on-peak and off-peak electricity price

(2) Approximate value in view of the defining parameters (Law decree 23/2010, DGEG, Nº5/2012)

Table 1: Energy costs

To each scenario, three alternatives were analyzed:

1. trigeneration runs 95% of the year, sells electricity at a fixed price
2. trigeneration runs 95% of the year, sells electricity at variable prices (peak/off peak)
3. trigeneration runs 71.4% of the year (peak periods), sells electricity at peak prices.

4. RESULTS AND DISCUSSION

This configuration, whilst exceeding the minimum required heat input to the AC, is the only that ensures enough power from the microturbines outtake to fully drive the AC (Table 2).

Scenario I	Alternative 1	Alternative 2	Alternative 3
Operating costs [€/year]	689.062	689.062	512.622
Annual savings [€/year]	597.695	609.969	462.402

Table 2: Scenario I annual operating cost and savings

To minimize waste heat from the prime movers, only two microturbines were employed with the remaining power required by the AC, provided by an auxiliary gas burner (Table 3).

Scenario II	Alternative 1	Alternative 2	Alternative 3
Operating costs [€/year]	501.785	501.785	378.853
Annual savings [€/year]	432.537	439.605	333.586

Table 3: Scenario II annual operating cost and savings

In this scenario an attempt was idealized to enhance profit, by adopting an ICE as prime mover (higher electrical efficiency - 42.9 vs. 33% of the microturbine) (Table 4):

Scenario III	Alternative 1	Alternative 2	Alternative 3
Operating costs [€/year]	1.261.366	1.261.366	921.411
Annual savings [€/year]	1.269.064	1.302.501	986.040

Table 4: Scenario III annual operating cost and savings

Although these results show a slightly positive net income, they are based on the assumption of a premium price of electricity sold to the grid, which would not be the case as the primary energy saving index is below the required minimum of 10%.

4.1 Further considerations

Tables 2 to 4 show that none of the proposed trigeneration alternatives are attractive. This can be further understood accounting for the COP relationship between the two cycles (Figure 4). In fact, most of the ammonia ACs installed throughout are in the MW range (comparatively higher COPs), and are also driven by "true" waste heat input. They are quite used for example, in coffee preservation (at -60ºC) and many other processes at set-points below -30ºC. For each unit of energy input to the AC it is observed that the CC output varies from 4 to 9 (-50 to 0ºC). The dashed line plotted in the secondary axis shows the relationship between the (fixed) electrical price paid by this company and the maximum price-to-be-profitable heat input to the AC. In other words, the required "spark gap", modified to account for each of the system's efficiencies and allowable energy prices is highlighted. Additionally, it is clear that in ACs a more negative set point temperature favors their competitiveness provided that an economical source of heat is available which was not the case at this site.

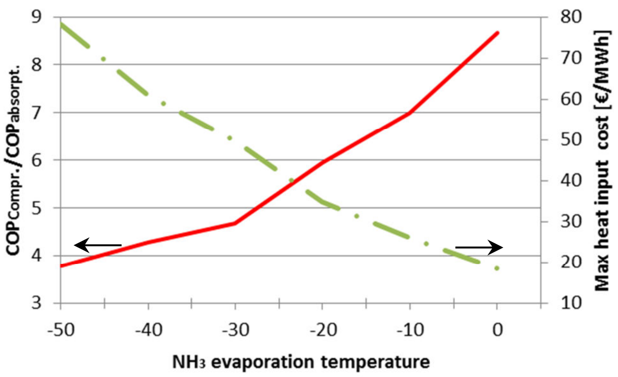

Figure 4: Relation between cycle COP's and required "spark gap" of energy to drive the trigeneration system

5. CONCLUSIONS

In this work, a prospective assessment was made aiming to replace a high efficiency but with high energy running costs CC with an ammonia AC. Three scenarios, each with three alternative configurations, were reviewed. Although scenarios I and II presented a minimum of 10% in primary energy savings, economics dictated that the trigeneration configurations studied were not competitive due to both energy cost and AC efficiency at the required temperature level. Given each of the system's COP at -30ºC, the *spark gap* would have to be lower than approximately 2.5. Sustaining the claims found throughout literature, the price difference between these competing energy forms represents the minimum required for trigeneration systems to be economically viable.

Although trigeneration for the deep freeze temperatures is hardly justifiable if no true waste heat is available, there has been an increased research effort in the past years dedicated to systems capable of achieving negative temperatures with higher efficiencies. It is foreseeable that if in the near future improvements in these systems are achieved, decreasing the current price spark gap through improved COP's, there will be a vast market (food companies from all ranks) to conquer. With it, one would also make a strong contribution to the reduction of primary energy requirements and Greenhouse Gas Emissions (GHG) through the widespread use of distributed trigeneration systems, thus lowering dependence from the grid (with all its inherent energy losses).

REFERENCES

[1] Banco de Portugal, Eurosistema, “Análise sectorial das indústrias alimentares”, Estudos da Central de Balanços (2011)

[2] IDAE. “Estrategia de Ahorro y Eficiencia Energética en España 2004 — 2012. Ministerio de Industria, Turismo y Comercio de España, (2012)

[3] J. Bassols, et al. “*Trigeneration in the food industry*”, *Appl Therm Eng*; Vol. 22, pp. 595-602, (2002)

[4] M. Moya, et al. “*Performance analysis of a trigeneration system based on a micro gas turbine and an air-cooled, indirect fired, ammonia-water absorption chiller”, Appl Energy*; Vol. 88, pp. 4424-4440, (2011)

[5] Seyfouri Z., Ameri M., “*Analysis of integrated compression-absorption refrigeration systems powered by a microturbine”, Int. J. Refrig*; Vol. 35, pp. 1639-1646, (2012)

[6] Deng J., Wang R.Z., Han G.Y. “*A review of thermally activated technologies for combined cooling, heating and power systems”; Prog. Energ Combust Sci*; Vol. 37, pp. 172-203, (2011)

ACKNOWLEDGMENTS

The authors acknowledge the contribution of the Project Inovenergy funding bodies and of all the Agrofood industries that cooperated with us so far.

inovcluster
Associação do Cluster
Agro-Industrial do Centro

COMPETE
PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

QREN
QUADRO
DE REFERÊNCIA
ESTRATÉGICO
NACIONAL
PORTUGAL 2007.2013

UNIÃO EUROPEIA
Fundo Europeu
de Desenvolvimento Regional