TECHNICAL AND ECONOMIC ANALYSIS OF ABSORPTION REFRIGERATION SYSTEMS RUNNING ON RENEWABLE ENERGY SOURCES IN THE BRAZILIAN AMAZON

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Abstract. Throughout the Brazilian Amazon there are many distant, isolated communities along riverbanks where electricity is not available at all. This state of affairs has implications for fishing, which is a major economic activity in the area. The fish product is subject to substantial losses due to a lack of refrigeration equipment. The present paper discusses the feasibility of implementing ammonia-water absorption refrigeration (AAR) facilities in these communities running on renewable energy sources; the alternative sources considered were solar energy and biomass. The former was selected because it would be a straightforward solution to the problem; the latter is held to be the most promising renewable energy sources in isolated communities. However, assuring a regular biomass supply requires setting up a related economic activity in the community. Simulation of these two cases was made using both a home written computer routine for the solar equipment and a commercially available software for the AAR cycle; actual weather data for the Amazon region were also used in the simulation. The economic analysis considered only the initial costs of these two systems due to the difficulties in assessing the operating costs of either system in this rather unusual context. As the simulations main results, the refrigeration capacity possible to be obtained throughout the year from the solar system and the corresponding fish product that could be preserved were calculated. In addition, a statement is also made regarding whether the solar solution is worth pursuing further as compared to the biomass gas fired AAR cycle.

Keywords: absorption refrigeration, solar energy, biomass, computer simulation, initial costs

1. INTRODUCTION

Amazonas is the largest state in Brazil, covering approximately 1,500,000 km^2 in the Brazilian Amazon. Except for a few larger towns and cities, the population is spread out along riverbanks in isolated communities. Therefore, the generation and distribution of electricity to these populations are faced with a number of difficulties spanning from management to technical issues. Extending power lines from the main population centers to distant communities is not feasible due to the peculiar geographic characteristics of the region and to the fact that low-income, isolated communities could not afford the final costs of electricity. According to Correia (2005), only 32 out of approximately 4600 communities in Amazonas are supplied with electricity from power plants belonging to Companhia Energética do Amazonas S.A. (CEAM), a subsidiary of Centrais Elétricas do Norte do Brasil S.A. (ELETRONORTE). CEAM is the federal government company in charge of electricity generation and distribution in the Amazonas State interior since 1997. The CEAM system is exclusively diesel based and is made of small and moderately sized units (150 kW through 3.5 MW). In addition, there are about 3000 small size (12.5 to 66 kW) independent electricity generators distributed throughout the isolated communities; however, most of them cannot be run continuously due to nonsteady fuel supply and non reliable maintenance. They are used mainly for activities such as evening classes and the like.

Operation of isolated systems in the Amazon is extremely difficult. Fuel for the diesel engines is distributed using waterways and, starting from Manaus, takes up to 40 days to reach some locations (Domingues, 2003). The use of renewable energy sources to drive electricity generators is not an obvious solution to the problem, either, despite its social and environmental advantages (Correia, 2005). High initial costs, the inexistence of small-scale energy conversion equipment, technologies not yet well established, and lack of information among local people involving these technologies are barriers to be overcome before renewable energy sources can be used regularly to meet the energy demands in the Amazon interior.

In the State capital city, Manaus, electricity generation and distribution are in charge of Manaus Energia S.A. (MESA), also a subsidiary of ELETRONORTE. The MESA system is mostly thermally based, constituted mainly of Rankine and Brayton cycles power plants and independently owned gas turbines and diesel engines generation units up to 15 MW in size. The MESA and CEAM systems are not interconnected, and CEAM units are also isolated from each other (Cartaxo *et al*., 2001). Manaus represents the largest isolated electric system in Brazil's northern region, gathering 400,000 consumers and with a demand profile similar to other heavily industrialized cities elsewhere in the country (Frota, 2005). However, the extremely high costs of the electricity generated by the MESA system require heavy subsidies from the federal government, which ultimately fall on taxpayers in the whole country. Moreover, most of

Manaus fuel power plants are nearing the end of their lifetime; in 2004 the energy supply was not able to keep pace with the high demand driven by the city's economic growth.

Dominguez (2003) carried out a study on the interconnection of isolated systems in the Brazilian Amazon to the national grid. The study showed that presently most systems cannot be made profitable to the point of justifying the capital invested in the interconnection, with the exception of those serving the capital cities of the states of Amazonas, Amapá, Acre, Rondônia, and Roraima. As a long-term solution to this problem, two major projects are under way, namely, extending power lines from the Tucuruí hydroelectric power plant to Manaus and Macapá (capital city of Amapá State) and building a gas pipeline from the Coari reserve, in the Solimões river basin, to Manaus. Figure 1 shows the possible interconnection route between the Tucuruí hydro power plant, Manaus, and Macapá. Once materialized, the 1800 km long interconnection not only will make Manaus and Macapá part of the national interconnected electric system, but also will serve around 30 other localities with an overall population of about two million people. Furthermore, this interconnection will make for a substantial reduction in the costs of the electricity used in Manaus. Even so, the Tucuruí-Manaus-Macapá interconnection alone will not solve the energy problem in Manaus. The 650 km long pipeline between Coari and Manaus will allow for a nine million m^3/day gas flow to the city's thermal power plant and isolated consumers. Side extensions of the pipeline to localities along its route are also planned. In the year 2004 the construction of the pipeline was analyzed regarding its environmental impact and its construction was approved (RIMA, 2004). The effective gas supply to Manaus will still require a formal agreement to be signed between PETROBRÁS (the national company in charge of oil and gas exploration in the Coari reserve) and Companhia de Gás do Amazonas − CIGÁS (the State gas distribution company). One can foresee the effective operation of the Coari-Manaus pipeline in the year 2008.

Even if electricity is soon made available to the inhabitants of the Amazon rain forest, these low-income populations cannot afford the final costs of electricity. In other words, a reliable and efficient energy supply program will only work in connection with social programs for sustainable economic growth in these areas (Correia, 2005). Of immediate concern is that fishing, a major economic activity in the Amazon, is subject to substantial losses, ranging from 15% to 30%, due to a lack of cold storage chambers and ice production equipment even in localities where electricity is available. In addition, fruit harvested from the jungle cannot be either properly stored or preprocessed. Therefore, the use of solar powered absorption refrigeration systems could help solve the fish and fruit conservation problem in isolated communities.

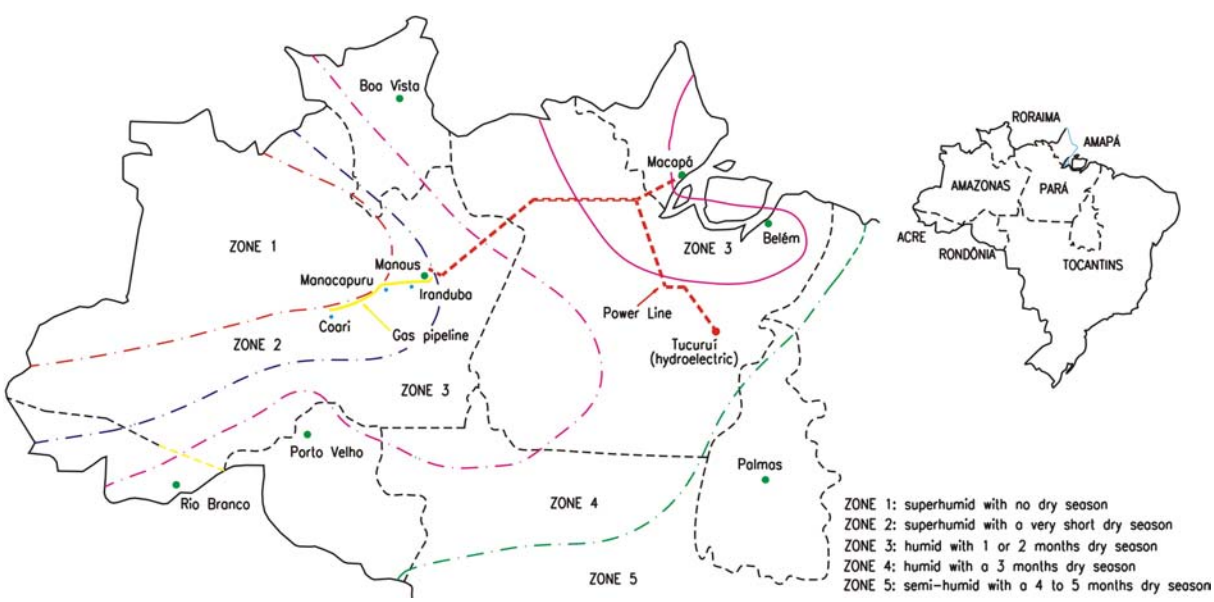

Figure 1. The Coari-Manaus gas pipeline, the Tucuruí-Manaus-Macapá electric interconnection, and the weather regimes in the Brazilian Amazon states.

Even though biomass is said to be the most promising renewable energy source in the Amazon interior (Nanni, 2005), electricity generation or simply running an absorption refrigeration cycle on biomass implies assuring a steady raw material supply associated with some local economic activity. Thus, the use of solar driven absorption cycles could be a more immediate solution to the problem; however, biomass and solar energy conversion are very different technologies with varying degrees of sufficiency in the national industry and the costs of both will have to be thoroughly checked before any system is actually built. The main goal of the present work is to assess the technical and economic feasibility of operating an absorption refrigeration cycle using hot water from a solar heater to produce ice for fish conservation. A comparison is made between the costs of the solar driven absorption system and a comparable biomass gas fired one. Due to the difficulties in assessing or putting a price on operating costs of either system in this rather unusual context, the financial analysis was restricted to the initial costs.

2. WETHER REGIMES IN THE BRAZILIAN AMAZON

The Brazilian Amazon is approximately 5,000,000 km^2 large, entirely covering the States of Acre, Amazonas, Roraima, Rondônia, Mato Grosso, Pará, Amapá, Tocantins, and part of Maranhão State. In spite of general public perception of a hot and humid climate, there is actually a clear time and spatial variation in weather conditions. The time variation is determined primarily by the rainfall pattern, the rainy season being characterized by a greater variability in solar radiation, relatively low dry bulb temperature, and very high humidity. The opposite holds true for the dry season. From the spatial point of view, one can identify five different weather regimes (Figure 1), namely, superhumid (Zone 1) with no dry season, superhumid with a very short dry season (Zone 2), humid with one to two months dry season (Zone 3), humid with a three-month dry season (Zone 4), and semi-humid with a four to five months dry season (Zone 5). Mean annual temperatures and relative humidity fluctuate between 24 and 27°C and 67 and 90%, respectively. Total sunshine hours in the region vary from 1500 to 2600 hr. Even though the present work is focused on the possibilities for solar driven absorption refrigeration cycles in Amazonas State, knowledge of the different weather regimes in the region will help extend the conclusions to other states.

3. ABSORPTION REFRIGERATION SYSTEMS

Absorption systems do not require the temperature of the heat source to be so high, thus making possible the use of waste heat from some industrial process or other low-quality heat source. This technology is therefore seen as environment friendly and a desirable substitute for vapor compression refrigeration machines. Despite the advantages of absorption refrigeration systems, the refrigeration equipment market is still dominated by compression chillers due to their lower initial cost and higher efficiency.

The most common absorption systems are $LiBr/H_2O$ and H_2O/NH_3, which are used in distinct application due to the different evaporation temperatures attained. Because water is used as the refrigerant, $LiBr/H_2O$ systems are limited to applications that do not require very low evaporation temperatures, e.g., comfort air conditioning. In contrast, H_2O/NH_3 systems, so called AAR systems, are used for food refrigeration, ice making, and similar applications because ammonia is the refrigerant and very low evaporation temperatures are possible. The coefficient of performance of $LiBr/H_2O$ systems usually decreases substantially when operated by heat sources at temperatures below 85 ^oC (Atmaca and Yigit, 2003; Ghaddar *et al*., 1997). The $LiBr/H_2O$ systems operate satisfactorily at a generator temperature of 88 ^oC to 93 ^oC, achievable by a flat plate solar collector, and exhibit a larger COP than AAR systems (Kreider and Kreith, 1982). In practice, the evaporator cannot operate at temperatures much below 4.5 ^oC, which are nonetheless within the range suitable for comfort air conditioning.

The COP of an AAR cycle is affected by its operating temperatures (evaporator, absorber, generator, and condenser temperatures) and its components irreversibilities. Regarding the COP variation with the generator temperature, an optimum was found to exist (Colonna and Gabrielli, 2003) and the temperature at this point was called optimal generation temperature (OGT). The OGT is influenced by the AAR components efficiencies, distillation column reflux, pressure drops, evaporator temperature difference and refrigerant concentration, and thermal operating conditions (evaporation, absorption, and condensation temperatures). Therefore, design improvement and control strategies to keep AARs close to their OGT regardless of variations in the refrigeration load and ambient conditions are crucial if they are to compete with vapor compression refrigeration systems.

Bulgan (1997) studied the use of low temperature (85 to 110°C) heat sources to drive AARs. The author considered the heat source temperature the primary variable and then simulated the influence on COP of many operating parameters including cooling water temperature. The simulations demonstrated that COP decreases rapidly with decreasing generator temperature, but a careful selection of the process parameters values could make for COP greater than 0.5 if cooling water at a suitable temperature is available. Nonetheless, process conditions for maximum efficiency will not be the same as those determined by an economic optimization criterion such as the rate of return. Bulgan (1997) then suggested that the optimization criterion could be to maximize the rate of return subject to the requirement of a minimum COP value. In this context, absorption refrigeration systems have been the object of several studies (e.g, Álvares and Trepp, 1987, Colle and Vidal, 2004, Fernandez-Seara and Vázquez, 2001, Florides *et al.*, 2002, Joud and Abdul-Ghafour, 2003, Li and Sumathy, 2002).

The major problems facing solar absorption cooling systems are its high initial cost, low system performance, and the relative low heat transfer rates that can be derived from solar radiation for operation over shorts periods (Li and Sumathy, 2000). Therefore, the optimization of the solar collector area and operating temperatures is among the first requirements for setting up limits within which solar absorption systems could become economically attractive (Colle and Vidal, 2004). In recent years, increasing costs of electricity worldwide and decreasing production costs of solar collectors in many countries are contributing to make solar refrigeration more economically attractive.

In this study, Cycle-Tempo software (Cycle-Tempo, 2006) was employed to simulate the operation of the absorption machine and determine its COP.

4. SYSTEM DESCRIPTION AND MODELING

Sales *et al*. (2005) assessed the technical and economic viability of running a $LiBr/H_2O$ absorption cycle using hot water from a solar heater and natural gas as the auxiliary energy source in southeast Brazil. The complete system (flat-plate solar collectors, storage tank, and absorption cycle) was modeled and a computer routine was written to predict its performance on an hourly basis. In the present case, one has an exclusively solar driven AAR cycle and it is no longer possible to use flat-plate solar collectors because of the high temperature level at which the useful heat has to be delivered to the generator. Therefore, the model by Sales *et al*. (2005) was modified to replace the flat-plate collectors with evacuated tube collectors (ETCs). The model so modified allowed for the hourly calculation of the useful heat transferred from the ETCs to the water in the tank. These results were then input to the Cycle-Tempo software for the simulation of the AAR chiller.

The AAR cycle simulated was based on that described by Colonna and Gabrielli (2003) and is shown in Figure 2. These authors considered the refrigerant pre-cooling for the single-stage AAR cycle as a means of increasing COP and thus the refrigeration capacity for the same recoverable heat. Values for the design operating temperatures adopted by Colonna and Gabrielli (2003) were adapted to this radically different application of AAR machines. However, values for the temperature differences in the heat exchangers and pump efficiency were maintained as they reflect common techno-economic design optimization for these components. Colonna and Gabrielli (2003) also found out that a generator outlet refrigerant temperature 15°C lower than the OGT maximizes refrigerant heat flow, which in their case corresponded to 120°C. Álvares and Trepp (1987) showed that a 120°C generator inlet temperature allowed for the highest annual solar fraction in their equipment while temperatures below 110°C caused a drastic reduction in COP. Accordingly, in the present case the restriction was imposed that the energy should be delivered to the generator at 130°C, thus ensuing 120°C minimum refrigerant temperature at the outlet. The evaporation temperature was set at -10°C. Another point to be kept in mind is that in the application under consideration all pumps would have to be driven by electricity from photovoltaic panels. Electric power consumption by the refrigerant and solution pumps is about 0.3 kW/TR (Herold, *et al.*, 2005).

The solar collectors and hot water storage tank were modeled following the formulation presented by Duffie and Beckman (1991). It follows that,

$$Q_u = A_c I \eta_c \tag{1}$$

where Q_u is the useful heat transferred to the water in the storage tank, A_c is the collector area, I is the hourly solar irradiation, and η_c is the collector efficiency given by:

$$\eta_c = F_R\left(\tau\alpha\right) - F_R U_L\left(\frac{T_{in} - T_a}{I}\right) \tag{2}$$

where T_{in} is the collector inlet water temperature, T_a is the ambient temperature, and $F_R U_L$ and $F_R(\tau\alpha)$ are parameters characteristic of the solar collectors (Duffie and Beckman, 1991).

For the evacuated tube collectors simulated, $F_R(\tau\alpha) = 0.82$ and $F_R U_L = 2.19$ W/m^2.^{o}C (Assilzadeh *et al.*, 2004). Assuming there is no stratification and the heat transfer rate to and from the storage tank to remain essentially constant over an appropriate time interval, Δt, the mean water temperature in the tank at the end of each time interval can be calculated from

$$T_{s,new} = T_{s,old} + \frac{\Delta t}{(Mc_p)_s}\left[Q_u - Q_L - (UA)_s\left(T_{s,old} - T_{as}\right)\right] \tag{3}$$

In this equation, Q_L is the energy extracted from the storage tank, M is the water mass in it, $(UA)_s$ is the tank overall heat transfer coefficient, and T_{as} is the ambient temperature where the tank is located.

In calculating the refrigeration load made possible by solar system (Figure 2), weather data for Manaus were used (SUNDATA, 1993). For calculations of the hourly solar radiation on the tilted collectors, RADIASOL software was used (RADIASOL, 2002). Despite different weather regimes in the Amazon as depicted in Figure 1, the simulation results are still valid as far as checking the feasibility of solar driven AAR machines is concerned. Of course, for design purposes weather data more representative of a specific location will have to be used if available.

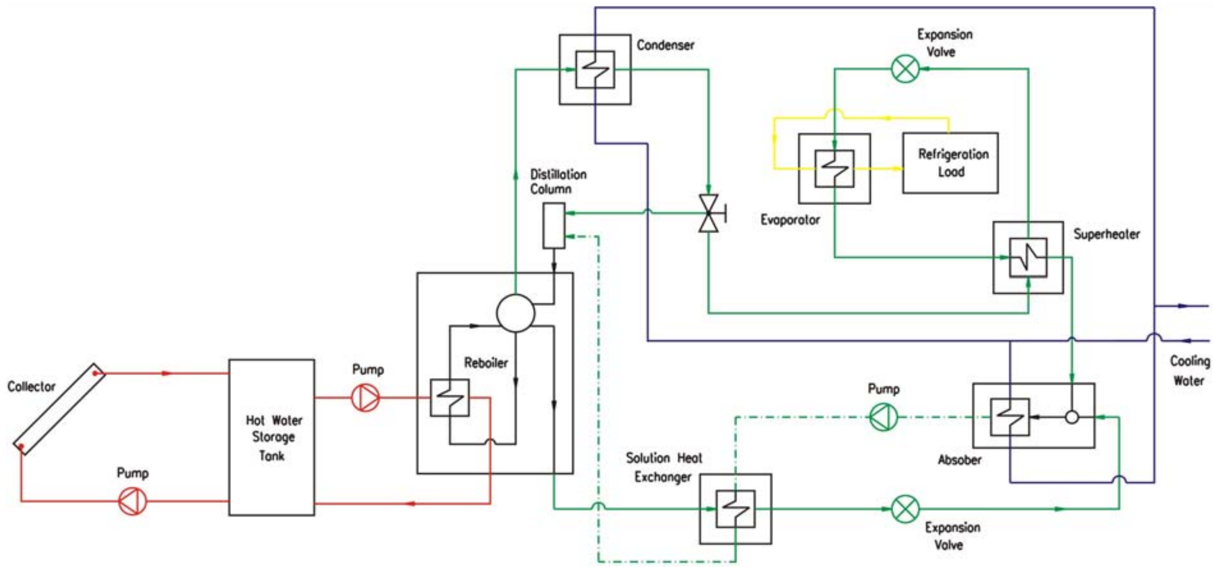

Figure 2. Schematic view of the solar driven AAR cycle.

Water will only flow from the storage tank to the absorption machine provided its temperature is above 130°C. The higher the flow rate, more rapidly energy is extracted from the storage tank and the temperature of the inlet water to the collectors drops; as a result its efficiency increases. For this reason, the mass flow rate m_L was obtained considering the energy extracted from the storage tank (Q_L) to correspond to the maximum energy transfer to the water in the collectors. This condition occurs for maximum efficiency and peak solar irradiation ($\eta_c = \eta_{max} = F_R(\tau\alpha)$ *and* $I = I_{max}$). It follows that,

$$m_L = \frac{I_{max} A_c F_R(\tau\alpha)}{c_{p,water}(T_{s,max} - T_{L,out})} \tag{4}$$

where $T_{s,max}$ is the highest water temperature in the storage tank with no energy extraction and $T_{L,out}$ is the water temperature at the generator outlet.

Once the refrigeration capacity (q_e) is obtained from the AAR simulation using Cycle-Tempo, the ice production mass rate (m_{ice}) can be calculated from

$$m_{ice} = \frac{q_e}{1.1(h_{water} - h_{ice})} \tag{5}$$

where h_{water} and h_{ice} are the enthalpy of water and enthalpy of ice, respectively. The former is dependent on the ambient conditions while the latter is usually set at -5°C for purposes of mechanical resistance. The 1.1 factor accounts for energy consumption for ice storage (Costa, 1982).

The largest daily fish production that can be preserved (m_{fish}) is then calculated as follows,

$$m_{fish} = \frac{(1-p) M_{ice}\left(c_{p,water} T_{f,\text{"}ice\text{"}} + L_{ice} - c_{p,ice} T_{i,ice}\right)}{c_{p,fish}\left(T_{i,fish} - T_{f,fish}\right)} \tag{6}$$

where $T_{i,ice}$ and $T_{i,fish}$ are the ice and fish initial temperatures, respectively; p is the heat transfer into the fish insulated container (estimated to be approximately 15% of the refrigeration load), M_{ice} is the daily ice production, $T_{f,\text{"}ice\text{"}}$ is the thawed ice final temperature, and L_{ice} is the latent heat of fusion.

5. ABSORPTION SYSTEM TECHNICAL AND ECONOMIC ANALYSIS

The relationship between the hot water storage tank volume and the collector area varies widely in the literature, from 13 to 200 liters/m^2 for flat-plate collectors. For the present case of ETC solar exchangers, the tank volume to be used with a given collector area was calculated by a trial-and-error procedure. For each storage tank volume assumed, the collector area was allowed to vary and results were obtained for the tank mean water temperature and the energy extracted from the tank under the restriction that this energy should be delivered to the AARs generator at 130°C minimum. It was observed that for volumes less than 500 liters, only a relatively small energy transfer rate can be extracted from the storage tank and a larger collector area per unit refrigeration capacity is necessary (Figure 3). For tank volumes of 1000 liters and larger, the longest time period for energy extraction was approximately six hours, normally from 10 am to 4 pm. The Figure 3 to Figure 6 summarizes the results obtained for the AAR operation parameters for the month of January, when the least insolation occurs (14.87 MJ/m^2.day average).

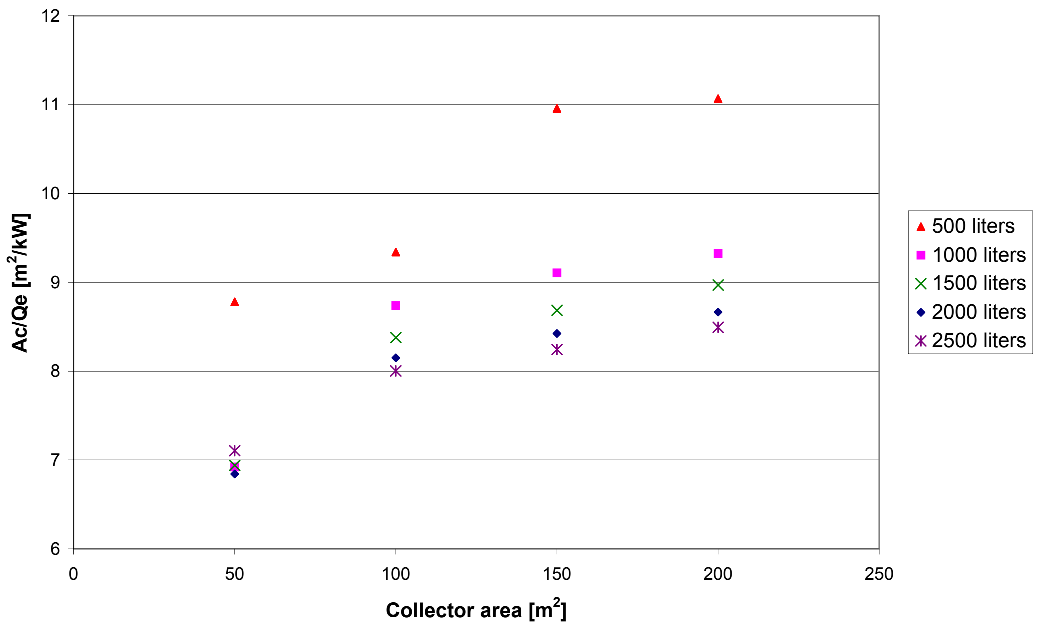

Figure 3. A_c/Q_e ratio as function of collector area.

Figure 3 shows that the collector area per unit refrigeration capacity decreases with increasing storage tank volume. Besides, the decrease in A_c/Q_e ratio is not significant for tank volumes larger than 2000 liters due to the lower water temperature. Figure 4 exhibits the cost of the solar system (collectors and storage tank) per unit mass of ice produced as a function of collector area. For a given collector area, the C_{sol}/M_{ice} ratio is not reduced significantly for tank volumes larger than 2000 liters. Hence, for collector areas in the 50 to 200 m^2 range, tank volumes larger than 2000 liters are not recommended.

In Figure 5, for a given collector area a storage tank volume can be identified beyond which ice production does not increase significantly. This observation was the basis for the information in Table 1.

The V_s/ A_c=10 liters/m^2 seems to be the most indicated for all ice production levels. In this case, the relationship between ice production and collector are is as shown in Figure 6.

The daily ice production, M_{ice}, was calculated using Eq. (5) assuming T_i = 30ºC and T_f = -5ºC. Heat transmission throughout the day to an isolated fish container was estimated to be approximately 15% of the ice refrigeration capacity. The result for COP obtained from the simulation using Cycle-Tempo was 0.59. The Maués trading post was taken as a reference for ice demand with an average 1.92 daily tons of fish (Cruz, 2004) and a corresponding 679 kg of ice required to keep the produce at 0ºC. The initial fish temperature was taken as 30ºC. From Figure 6, it can be seen that a 141 m^2 collector area and a 1410 liters storage tank would be required. The Table 2 summarizes the results obtained for the AAR operation parameters for the month of April in Manaus, when the least insolation occurs (16.02 MJ/m^{2}day average). It was then possible to determine, for each month of the year, typical hourly profiles of the mean water temperature in the tank and the energy extracted to the AAR generator, which in turn allowed for the refrigeration capacity. Table 3 summarizes the results obtained for the AAR operation parameters for the month of September in Manaus, when the greatest insolation occurs (20.30 MJ/m^{2}day average).

Table 4 summarizes the results for the equipment initial costs. Estimates for the unitary costs of the AARs and auxiliary equipment for ice production, such as ice trays and grinders, were taken from Cruz (2004); these are believed to be more representative of the Amazon region refrigeration market. Unitary costs for the ETCs and hot water storage tank were taken from Assilzadeh *et al.* (2004). Costs estimates for the photovoltaic panels were obtained from Heliodinâmica (2006).

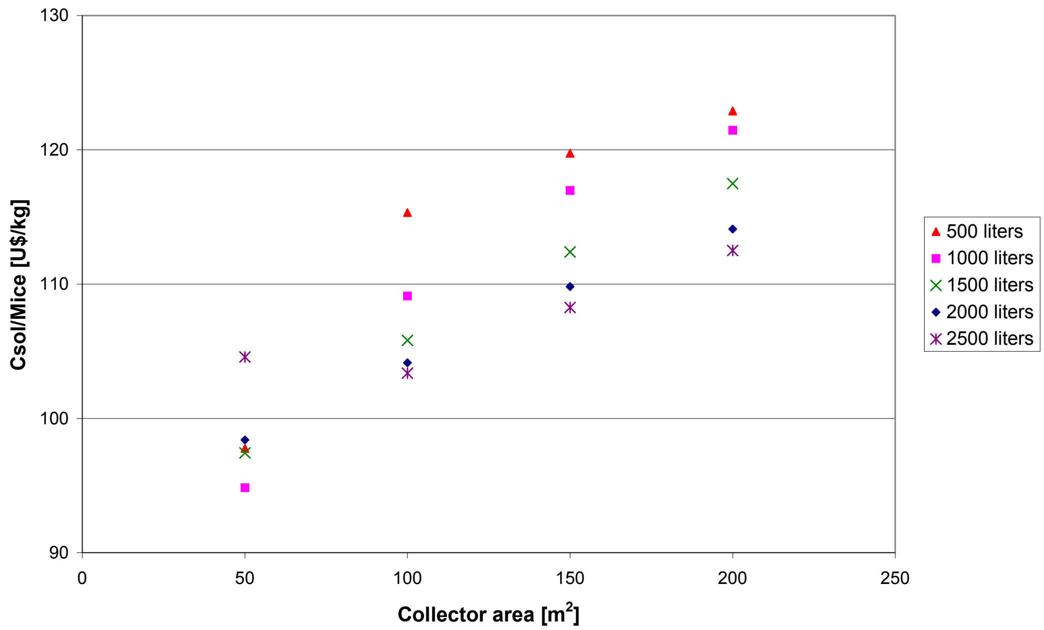

Figure 4. C_{sol}/M_{ice} ratio as function of collector area.

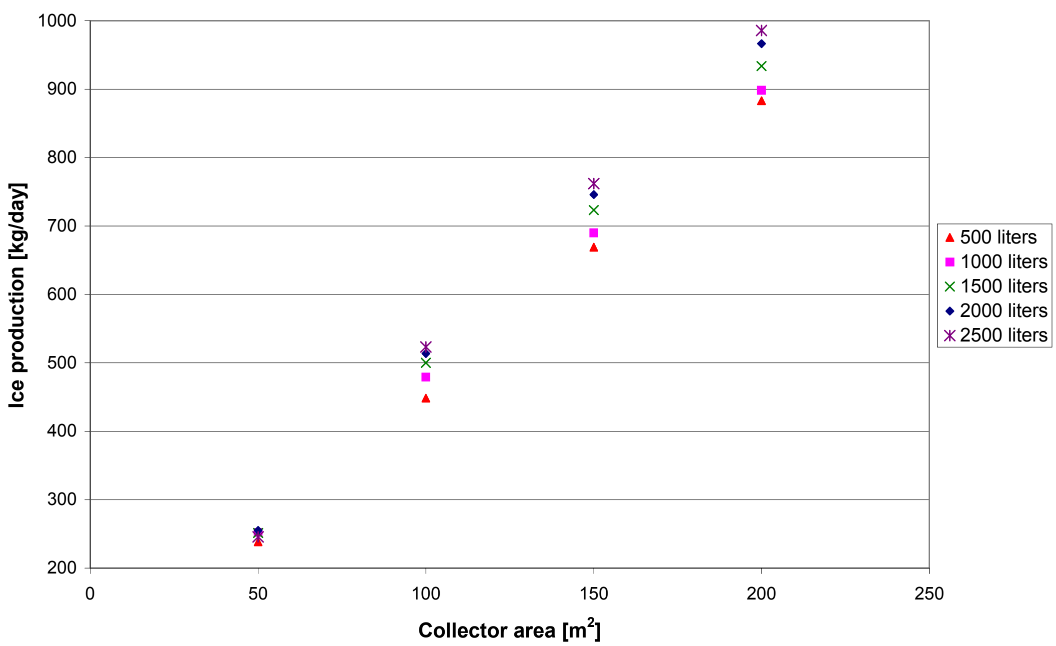

Figure 5. Daily ice production as function of collector area and storage tank volume.

Table 1. Solar system specifications for selected ice production levels.

A_c [m^2]	V_s [liters]	V_s/A_c [liter/ m^2]	m_L [kg/s]	M_{ice} [kg/day]
50	500	10	0.0647	238.5
100	1000	10	0.1290	479.4
150	1500	10	0.1929	723.4
200	2000	10	0.2569	966.6

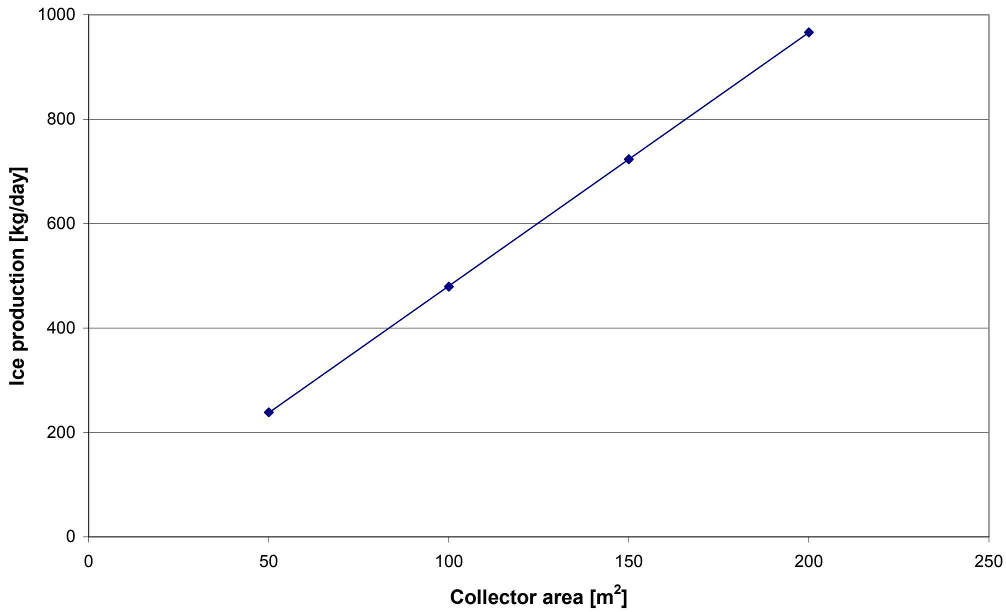

Figure 6. Daily ice production as function of collector area for V_s/A_c = 10 liters/m^2.

Next, considering a biomass driven chiller, a quotation was obtained for a fire-tube boiler to replace the ETCs and storage tank; the fuel could be cupuaçu shells. Cupuaçu is a fruit typical of the Amazon region whose extraction and trade also represent a significant economic activity in some places. The boiler specifications were made to be compatible with the same AAR cycle simulated in the solar system. The analysis showed the cost of the solar refrigeration system to be almost three times that of the biomass gas fired one. However, one should bear in mind that the biomass driven AAR cycle would require a fairly regular supply of cupuaçu shells. Anyway, the relatively high initial cost of the solar system is a barrier to its widespread use in the Amazon.

Table 2. Results for the solar driven AAR cycle operation in Manaus during the month of January.

V_s [liters]	A_c [m^2]	m_L [kg/s]	Operation Time [hr/day]	Q_L [MJ]	Q_e [MJ]	$q_{e,max}$ [TR]	COP	M_{ice} [kg/day]	M_{fish} [kg/day
1410	141	0.1814	6	598.72	350.22	5.4	0.5908	679.3	1920.0

Table 3. Results for the solar driven AAR cycle operation in Manaus during the month of September.

V_s [liters]	A_c [m^2]	m_L [kg/s]	Operation Time [hr/day]	Q_L [MJ]	Q_e [MJ]	$q_{e,max}$ [TR]	COP	M_{ice} [kg/day]	M_{fish} [kg/day]
1410	141	0.1596	6	881.55	520.82	7.7	0.5908	1010.0	2857.6

Table 4. Initial costs for the solar and the biomass driven AAR cycles.

	Solar Driven AAR Cycle					**Biomass Driven AAR Cycle**			
	AAR	**Aux. Equip.**	**ETCs**	**Storage Tank**	**Photovolt. Pumping**	**AAR**	**Aux. Equip.**	**Boiler**	**Photovolt. Pumping**
Unitary Cost	3,700 U$/TR	1,100 U$/TR	568 U$/m^2	1.19 U$/liter	10.23 U$/W	3,700 U$/TR	1,100 U$/TR	-	10.23 U$/W
Cost [U$]	28,490	8,470	80,088	1,678	13,244	28,490	8,470	4,500	13,244
TOTAL [U$]	131,970					54,704			

6. CONCLUSIONS

The use of solar powered absorption refrigeration systems in the Brazilian Amazon was investigated. A solar refrigeration system with a141 m^2 collector area, 1410 liters storage tank and q_e = 7.7 TR is capable of producing up to 1010 kg of ice per day throughout the year in the climatic conditions of Manaus. This ice production rate represents the joint fishing production of some communities in the Amazon interior. If another refrigeration capacity is selected, the V_s/A_c=10 liters/m^2 still seems to be the most indicated for decreasing costs and improving collector efficiency.

The initial cost of the solar refrigeration system is almost 2.5 times that of the biomass gas fired one. However, one should bear in mind that the biomass driven AAR cycle requires a fairly regular supply of biomass. Anyway, the relatively high initial cost of the solar system is a barrier to its widespread use in the Amazon.

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