23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

Exergetic study of a hybrid photovoltaic and liquid air system

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Abstract. *This paper presents an energetic and exergetic analysis of a hybrid system and energy storage while uses photovoltaic panels and liquid air. The system uses the Linde cycle and is comprised of a compressor/turbine, heat exchangers, expansion valves, a pump and a cryogenic tank. Photovoltaic panels feed the compressor partially, storing the supplied power. The focus of this study was analyzing the relation between the solar energy of the region of Belo Horizonte, located in the state of Minas Gerais, Brazil, and the storage efficiency by a cryogenic system. The results are discussed and presented in the form of graphs, tables and performance evaluations to highlight the solar variability influence in the generation and storage.*

Keywords: *Cryogenic Energy Storage, Solar Energy, Hybrid Power Plants, Liquid air Energy Storage*

1. INTRODUCTION

The development of new technologies along the years has been crucial to supply the energy demand in the industry. Recently 15% of the Brazilian population, comprised about 25 million people, live without access to electric energy (Silveira *et al.*, 2013; Diniz *et al.*, 2011). It is necessary a large-scale renewable power plants and incentive policies to the development of new technologies. Studies estimate that in a short term, electric energy based on the generation through fossil fuels will need to be replaced by renewable sources, like solar and wind (Ameel *et al.*, 2013). Renewable energy contributes with 11% of the total and it is expected that this will raise up to 60% in 2070 (Li *et al.*, 2012).

Currently the HPS (Hydroelectric Power Stations), UES (Undi-Electric Power Stations), SHP (Small Hydroelectric Plant) and HEP (Hydroelectric Plants), compose the biggest energy generating sources in Brazil, corresponding to almost 67% of the total production. The portion of energy given by the WPP (Windmill Power Plant) and PVP (Photovoltaic Power Plant), represents 2.91%. TEP (Thermoelectric Power Plants) and TNP (Thermonuclear Power Plants), 30.11% (ANEEL, 2014).

In near future, there will be a great tendency to increase the renewable sources, mainly energy based on water, wind and solar, corresponding to 87.42% of the total. As one of the consequences, the fossil sources will decrease significantly, but in future, fossil sources will advance to 32.61% of the total generation.

As a consequence of these tendencies, one of the most attractive possibility today is integrating and using several alternative sources. The main idea is to utilize the natural availability for storage, and afterward, according to the demand or contractual agreements reuse this energy in of peak periods (Ameel *et al.*, 2013).

Within this scenario, a hybrid system is presented using solar photovoltaic energy and cryogenic energy storage (CES).

The choice of Belo Horizonte due to the fact that is the location of the Federal University of Minas Gerais (UFMG).

CES system must work in a very specific condition that is linked with local temperature and capacity to predict the weather for short period times. Some parallel studies shall be done for the completeness of this one.

First CES system dates from 1900 (Akhusrst, 2013), when the Tripler Liquid Air Company was created to design a liquid air system for vehicles. During the Oil crisis in the 1970‘s, come back again the enthusiasm on cryogenic cars, as well as the air liquefaction as a storing (Smith, 1977). In literature (Li *et al.*, 2010; Chen *et al.*, 2009), the term CES (Akhusrst, 2013), or LAES (liquid air energy storage), is generally applied to refer to the storing of liquefied

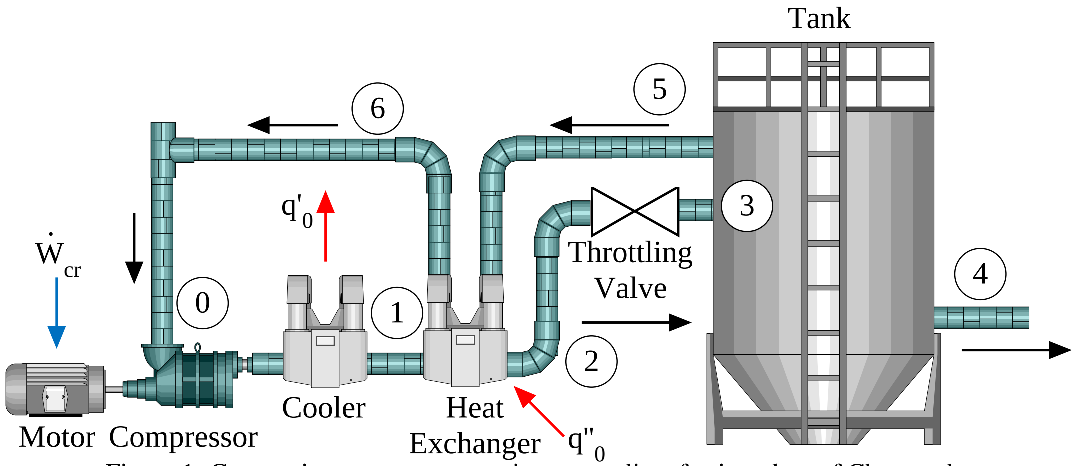

Figure 1. Cryogenic energy storage using a pure liquefaction plant of Chen cycle

air. Nowadays, hydrogen and nitrogen/air are the two most promising alternatives of working fluids for CES (Sander *et al.*, 2012; Li *et al.*, 2010). Comparing hydrogen and nitrogen/air for energy storage, concludes that both have similar efficiencies. The air is more competitive as energy accumulator/generator in terms of costs. Recently, Akhusrst (Akhusrst, 2013) published a report about the use of liquid air in energy transportation systems, indicating the important potential of CES.

The efficiency of CES during the liquefaction process is between 11% and 50%. After the liquefaction, the liquefied air can be converted into electricity. This process has a great potential to lose energy to the atmosphere due to the cryogenic temperature, resulting in a low efficiency (40% maximum). To solve this problem, Chen et al. (Chen *et al.*, 2009) created a patent to improve the conversion process, which indicates a considerable advance. AMEEL et al. (Ameel *et al.*, 2013) simulated the cycle proposed by Chen et al. and concluded that this system is too sensitive to the heat exchanger, compressor, and turbine efficiencies. The authors concluded that this cycle reaches a maximum efficiency of 63.7%, considering an expansion at 400 K.

The CES can be considered an open cycle, once the air does not pass by all the thermodynamic cycle, as occurs in Brayton's cycle. Another important similarity to Brayton's cycle is the great quantity of necessary work, due to the use of compressors. In this type of system, the overall efficiency decrease rapidly with the decrease of the compressor, heat exchanger, and turbine efficiencies, as observed by AMEEL et al. (Ameel *et al.*, 2013).

2. Methodology

2.1 Cryogenic storing system

Linde cycle was chosen for a viability analysis at the hybrid CES-Photovoltaic system. According to the Figure 1, The air was first compressed at a pressure of 20MPa. With the rise of the air temperature due to the compression process, a cooler decrease its temperature. The air enters in the primary heat exchanger in countercurrent with the outgoing colder products. The air pass through a throttle valve and undergoing an isenthalpic process with a slight decrease in temperature. The cooled air goes to the tank and returns to the heat exchanger. After a long period or time, the decrease in temperature is sufficiently to liquefy and produces liquid air.

Chen cycle (Chen *et al.*, 2009) explores a more complex system that uses stored liquid air to generate energy through an expansion turbine but for this study the analysis cover only the liquefaction processes without generation.

2.1.1 Energetic analysis

There are several ways to calculate the work done by the compressor. For this work, a reversible and isothermal process was considered. The energy needed for the compression is given by the equation 1:

$$W_{iso} = m_a R T_0 ln \frac{P_1}{P_0} \tag{1}$$

Where m_a is the mass of input air, in kg, R is the universal constant for gases, T_0 is the dead state temperature, in K, P_0 e P_1 are, respectively, the compressor input and output pressure, in KPa, and W_{iso} is the needed work for isothermal process, in kJ. Using the mechanical, electrical and isothermal yield it is possible to deduct an equation for the input energy in the compressor (Equation 2):

$$W_{CES} = \frac{W_{iso}}{\eta_m \eta_e \eta_{iso}} = \frac{W_{iso}}{\eta_t} \tag{2}$$

With η_m, η_e, η_{iso} e η_t are respectively, the mechanical, electrical, isothermal and total efficiency and W_{CES} being the real work done by the compressor, in kJ.

Through an energy balance in the regions that include the compressor and the cooler, expansion valve and the storage tank, it is possible through the Equations 3 e 4, to calculate the yield and quality:

$$z = \frac{h_6 - h_1 - q_{he}}{h_6 - h_4} \tag{3}$$

$$x = \frac{q_{he} + h_1 - h_4}{h_6 - h_4} \tag{4}$$

Where x e z are, respectively, the quality and yield, and h_1, h_4 and h_6 are the specific enthalpies of the air at each point shown in Figure 1, in kJ/kg and q_{he} is the heat leak, in kJ/kg.

2.1.2 Exergetic analysis

The specific and total exergy are given by the Equations 5 e 6:

$$\varepsilon = (h - h_0) - T_0(s - s_0) \tag{5}$$

$$E = m_a \varepsilon \tag{6}$$

Where ε is the specific exergy, in kJ/kg, E is the total exergy, in kJ, h_0 and h are, respectively, the dead state and a general specific enthalpy, in kJ/kg, and s and s_0 are, respectively, the specific entropy at a given point and the dead state specific entropy, in $kJ/kg.K$.

The irreversibility calculation between each system is given by the Equations 7, 8 and 9.

$$_0\sigma_1 = W_{CES} - E_1 \tag{7}$$

$$\sigma_{he} = (E_5 - E_6) + (E_1 - E_2) \tag{8}$$

$$_2\sigma_3 = E_2 - E_3 \tag{9}$$

This processes rational efficiency (Ψ) is given by the Equation 10:

$$\Psi = \frac{E_4}{W_{CES}} \tag{10}$$

2.2 Solar photovoltaic energy

The photovoltaic cells are composed by solar cells manufactured of light-absorbing material (Joshi *et al.*, 2009). The photovoltaic cells convert solar energy directly to electrical energy, by a phenomenon called photovoltaic effect. This effect was perceived in the first time in 1839 by Becquerel Razykov *et al.* (2011), and ever since this knowledge is used to the improvement of solar technology.

The solar panels production grew exponentially in the last decade (Timilsina *et al.*, 2012), and nowadays have grown about 35% to 40% a year (Razykov *et al.*, 2011). The most common types of solar panels in the market are the crystalline silicon (monocrystalline and polycrystalline) responsible for 87% of the world's production (Tyagi *et al.*, 2013). The polycrystalline have a lower manufacturing cost compared with monocrystalline, but lower yield efficiency. The first show yield efficiencies in the range of 12% and 15% while the second 15% a 22%. Those yields values are from market models.

Another monocrystalline material is possible, the GaAs (gallium arsenide). The GaAs panels are mostly used in aerospace applications, and, therefore, have a higher manufacturing cost, however, show high yields efficiencies, around 25% (Razykov *et al.*, 2011).

Another type of solar cells materials is the thin film, responsible for 13% of the world's production (Tyagi *et al.*, 2013). The thin film cost is lower when compared to the crystalline silicon, but the yield efficiency is lower. The most common thin films are of amorphous silicon, Cds (Cadmus sulfide)/ CdTe (Cadmus telluride) and CIS (Copper indium diselenide)/ CIGS (Copper-indium-gallium-selenium). The amorphous silicon panels are the most manufactured, due to its higher yield in this category, about 6

According to the Equation 11, the photovoltaic cells efficiency (η_f) is given by:

$$\eta_f = \frac{W_f}{I} \tag{11}$$

Where I is the incident solar radiation and W_f is the work given by the photovoltaic cell.

2.2.1 Exergetic Analysis

In the exergetic analysis of the conversion processes of the solar irradiation into electric current, the only generated irreversibilities are caused by non-absorption of available energy, given by the Equation 12.

$$\sigma_f = (1 - \eta_f)I \tag{12}$$

Where σ_f is the exergy destroyed in the conversion process.

2.3 Hybrid System

At the junction of the two systems in the study, the energetic and exergetic behavior shows the characteristics of the two systems and a supply source in common, the solar radiation. The equation 13, as a consequence of the Equations 2 and 3, describes the relation between the needed radiation for a quantity of air to liquefy and the other system input variables.

$$I = \frac{m_l R T_0 ln \frac{P_1}{P_0}}{z \eta_m \eta_e \eta_{iso} \eta_f} \tag{13}$$

Where m_l is the mass of liquefied air, in kg.

Through the Equation 12 and the exergic analysis related to each system, it is possible to obtain the expected results in the proposed study.

3. Uncertainty Analysis

The solar incidence and temperature information was received from the automatic weather station (AWS) from the National Institute of Meteorology (INMET - Instituto Nacional de Meteorologia), without statistic treatment. According with technical note No. 001/2011 (INMET, 2011) Vaisala MAWS 301 is the equipment used in INMET's AWS. To estimate the uncertainty of solar radiation and ambient temperature measurement, Vaisala sensors for the AWS MAWS 301 were studied.

A PT 100 transducer of Vaisala, model QMH102, was indicated to be used in the AWS MAWS 301 to the ambient temperature measurement (Vaisala, 2014b). The expanded uncertainty was provided directly in the instrument datasheet. The provided value was ±0,2 °C (Vaisala, 2014a). The solar radiation sensor indicated to AWS Vaisala MAWS 301 was the pyranometer QMS102. The uncertainty sources inherent to the radiation value measured was presented in the instrument datasheet of each component as shown:

- Temperature dependence: 6% (-10 °C to +40°C)
- Non-stability: 7% (1% per year of the AWS operation)
- Non-linearity: 2,5% up to 100 W/m^2

The uncertainty sources above were used to determine the combined uncertainty. It was considered that all sources are statistically independent. To the expanded uncertainty was considered k= 2, for 95% level of confidence. This way, the value found for the expanded uncertainty was estimated in 8,16% over measurement values to solar radiation.

4. Modeling

Based on the equations detailed in Section 2, a parametric study was aiming evaluate losses and gains obtained by the storing process using sun as main source. For this, two software were used: MatLab and EES. Air temperature, radiation and atmospheric pressure data were collected hourly by the National Institute of Meteorology (INMET) during the year 2013 at the automatic station located at the Ecological Station of the Federal University of Minas Gerais, according to data:

- Station: Belo Horizonte - Pampulha-A521
- Code OMM: 86800
- Opened in: 10/10/2006
- Latitude: -19.883945°
- Longitude: -43.969397°

For the simulation the following data was used, being some suggested by Kotas Kotas (2012), as follow:

- Environment, $P_0 = 91,91\ kPa$, T_0
- Heat exchanger input temperature, $T_1 = T_0$
- Compressor output pressure, $P_1 = 20000\ kPa$
- Air output temperature, $T_6 = T_0 - 5$
- Liquid air output temperature, $T_4 = -194\ °C$
- $\eta_e = 0,95$
- $\eta_m = 0,90$
- $\eta_{iso} = 0,70$
- $\eta_f = 0,16$
- $A_f = 500\ m^2$
- Only 50% of the solar radiation is available for storage
- The heat exchanger loses heat at a rate of $q_{he} = 2,1\ kJ/kg$
- The kinetic and potential components are negligible

The data acquired in 2013 was analyzed hourly. It is important to emphasize that as a feasibility study it is admitted that the compressor attends all flows and pressures available presenting always the same yields.

5. Results

The results obtained in this study are sufficient to characterize not only the operation of a particular case, but also the viability of a hybrid system that uses the sun and the liquid air. Considering only 50% of the solar energy available for storage, the results, initially, reveal the possibility of several types of improvement and new models that combine different forms of renewable energy.

The Figure 2 shows the incident solar radiation rate in terms of days of the year and hours of the day. A huge variation of solar radiation coming from the sun is noted. The curve reveals, at the same time, a significant energy quantity mainly at the beginning and the end of the year, which corresponds to summertime.

In the Figure 3 it is possible to realize the huge solar radiation instability, being it null at morning and night period. Periods with a greater amount of available energy are focused basically near midday. November 19th at 01:00 PM was the day of the year which presented the highest peak.

Similar to the solar radiation distribution curve, the Figure 4 presents the quantity of liquid stored in terms of days of the year and hours. According to the results, it is noticeable that the periods and hours corresponding to the higher quantity of stored liquid are exactly those in which there were solar radiation peaks.

According to the Figures 5 and 2 and the conditions exposed in the methodology, it is possible to observe that the periods of solar peaks corresponds to the highest liquid store. Regions with this characteristic can be favorable to the CES. The day and hour of the year that correspond to the greatest storage of liquid is October 13 at 09:00 PM.

The system efficiency varies according to the solar incidence and is showed by Figure 6. The rational efficiency is one of the most important parameters that is possible to extract from this study. According to the results shown, it follows almost the same value through the year, without oscillating significantly during season changes and solar radiation peaks. The curve reaches a maximum peak and follows constantly during the day.

The major amount of the energy provided by the sun is lost to the environment, being the day of most efficiency corresponds to July 7, at 07:00 AM. It is important to emphasize that the efficiency peaks occurs predominantly in the morning period, according to Figure 7. This is due mainly because of the thermal inertia accumulated during the day that has as main consequence the increase in the environment temperature.

As shown in Figure 8, the major part of the losses that occurs in this system correspond to the photovoltaic panels. An improve in the efficiency of photovoltaic cells is fundamental, not only for the system in this study, but for all future applications that aim at absorbing and transforming solar energy. In a general way, 84% of the losses are due to the extremely low conversion efficiency for solar radiation into electric energy, following the expansion valve with 6,94%, the compressor, with 6,42% and the heat exchanger with 1,83%.

The Figure 9 shows the Leveled Cost of Energy of the photovoltaic panels and it is a result of the compilation of several articles made by the Transparent Cost Database (OpenEI, 2014). This value is an estimate of the cost that includes

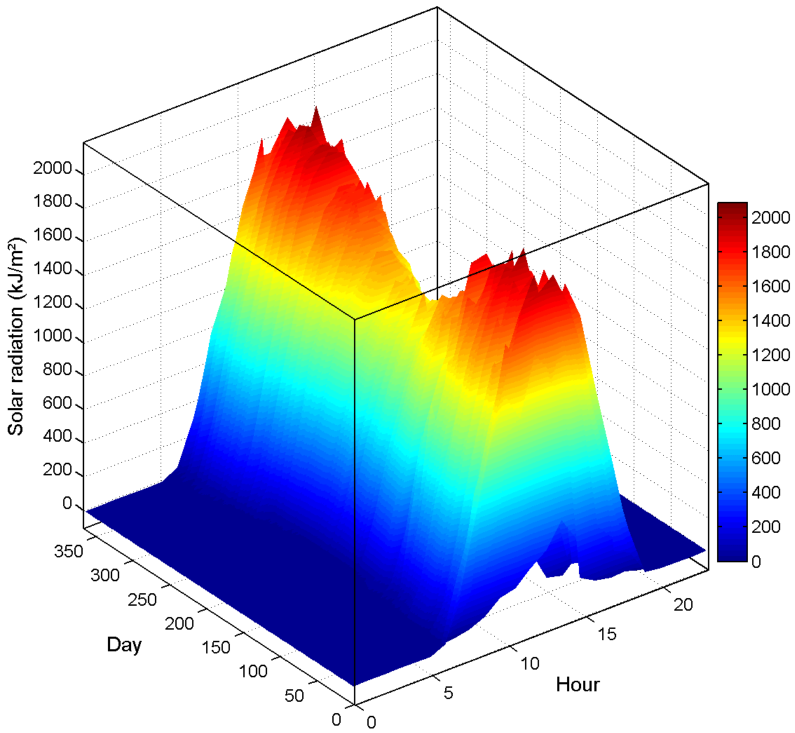

Figure 2. Available solar radiation to storage (a)

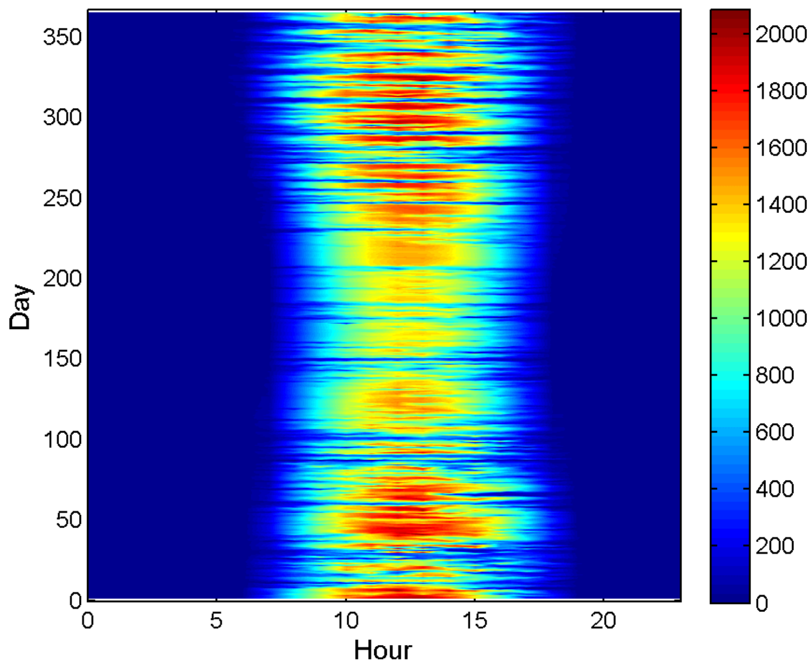

Figure 3. Available solar radiation to storage (b)

the financial return of the initial investment and the operational cost. An increasing fall at the investments return can be observed, which does not suggest, necessarily, that the solar technology had not been impractical in its featured period. The economic and currency fluctuation also affect this data.

Since the solar panels have been the main responsible for the energy losses, hybrid systems, as shown in this study, have economic indexes strongly attached to its efficiency. With the development of this new technology at lower costs and stable economy, the future of hybrid systems that combine photovoltaic cells has a promising economic return in the group of renewable energies.

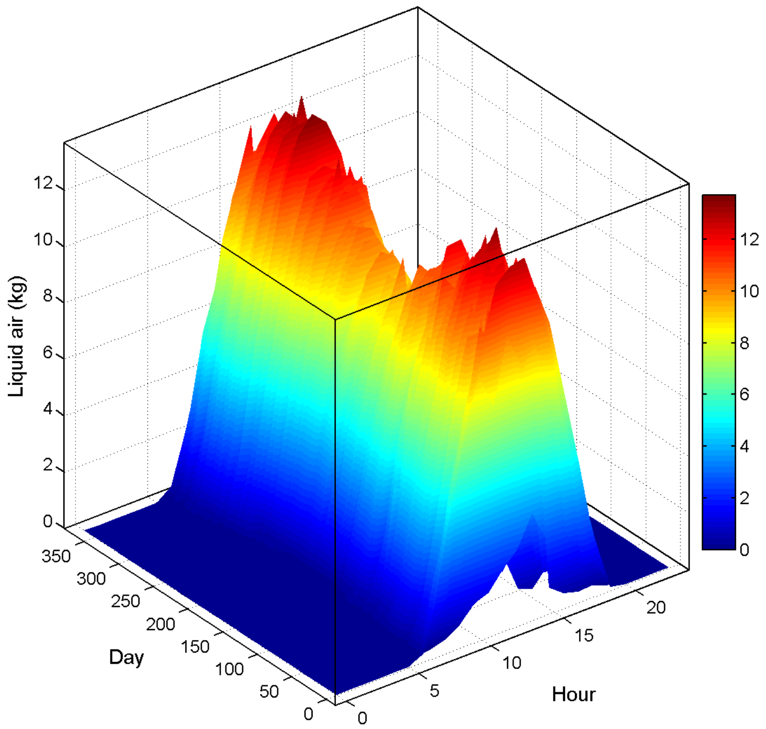

Figure 4. Stored liquid air (a)

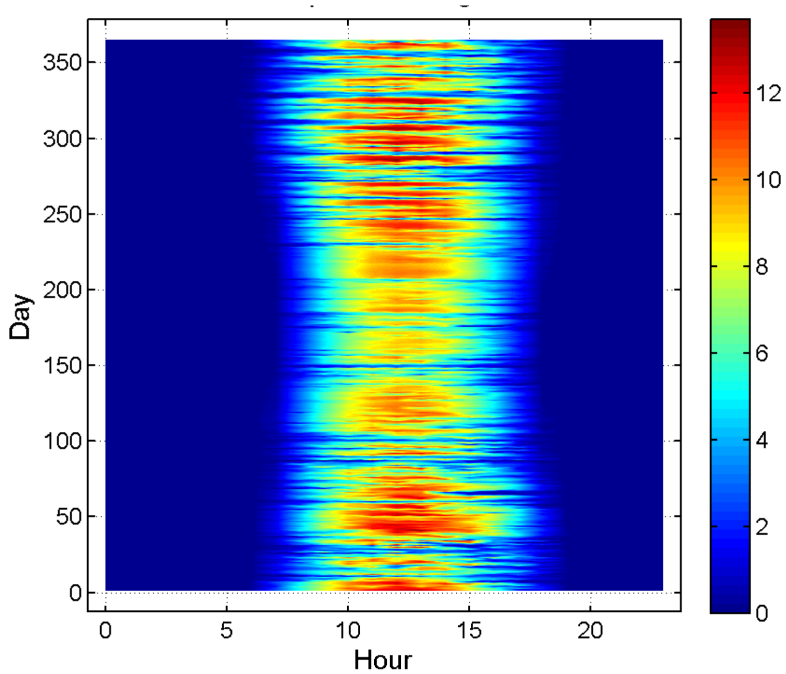

Figure 5. Stored liquid air (b)

6. Conclusion

The photovoltaic cells present an efficiency that significantly compromises the storing energy when used with the cryogenic energy storage. In spite of the solar energy being plentiful, it is necessary to evaluate its implantation in a very careful way, specially by the availability of obtaining the desired return, additionally to all the other characteristics present in this system, such as: sudden fluctuations and seasonal variability.

The region of Belo Horizonte, MG, as a start point for this study, showed that the solar energy availability might overcome the losses that generate irreversibility in the system. It is possible that Brazilian regions, like the northeast that offer more solar radiation by square meter might present operation improvements, however, a study that attests its viability

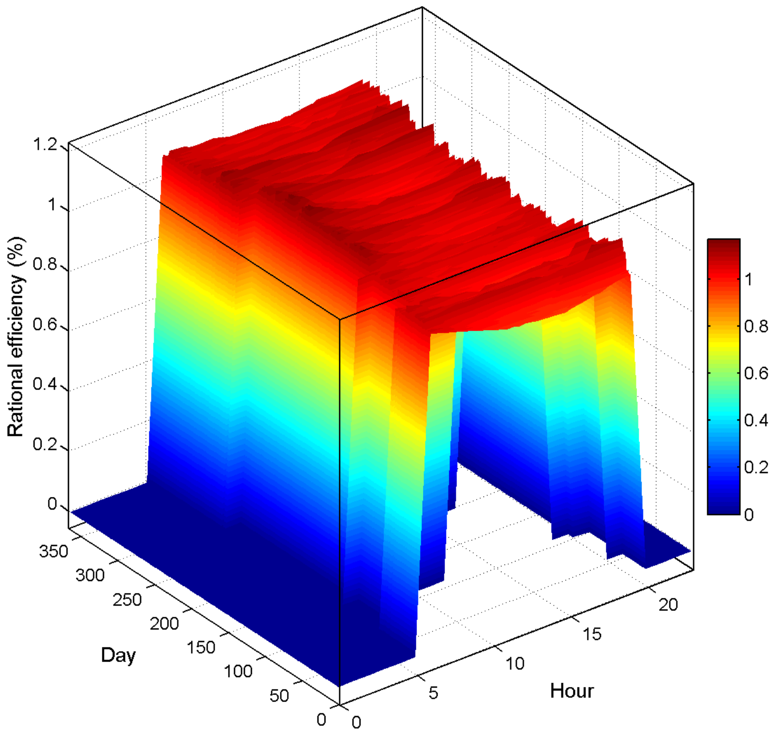

Figure 6. Rational efficiency (a)

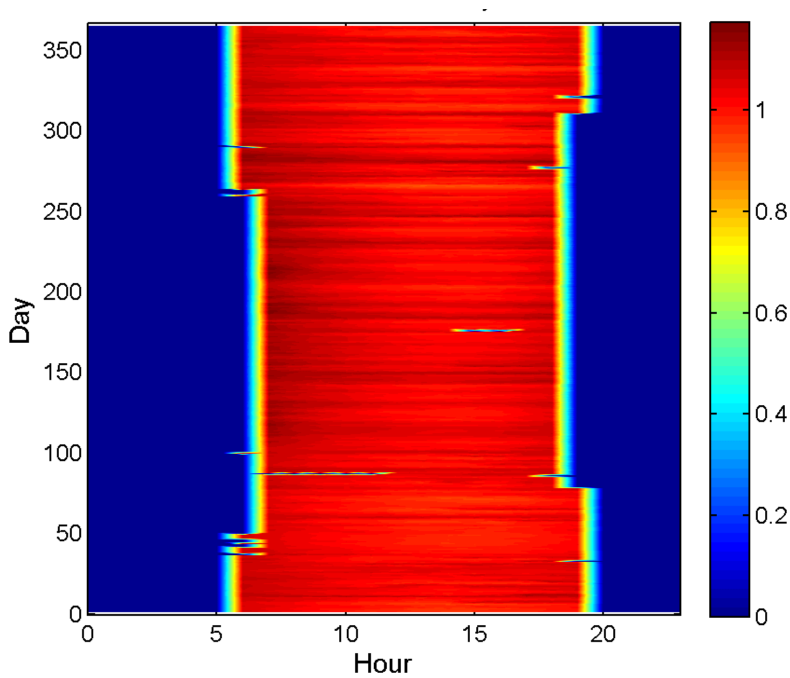

Figure 7. Rational efficiency (b)

is necessary.

It is important to notice that the stored energy will not necessarily be the same when produced during the generation. Besides the inherent losses in the generation cycle, the sun, as an influence in the exergy destruction, may be used by solar collectors to raise the air temperature and consequently the output energy.

It is also necessary to investigate the results according the actual operating characteristics of the compressor, which necessarily must fit the projects conditions. In this study, it was considered that the compressor admits equal pressures, flows and efficiency for each operation point stipulated in the result achievement process.

CES is a system that presents a high energy density, adequate to be used with abundant sources of energy and processes

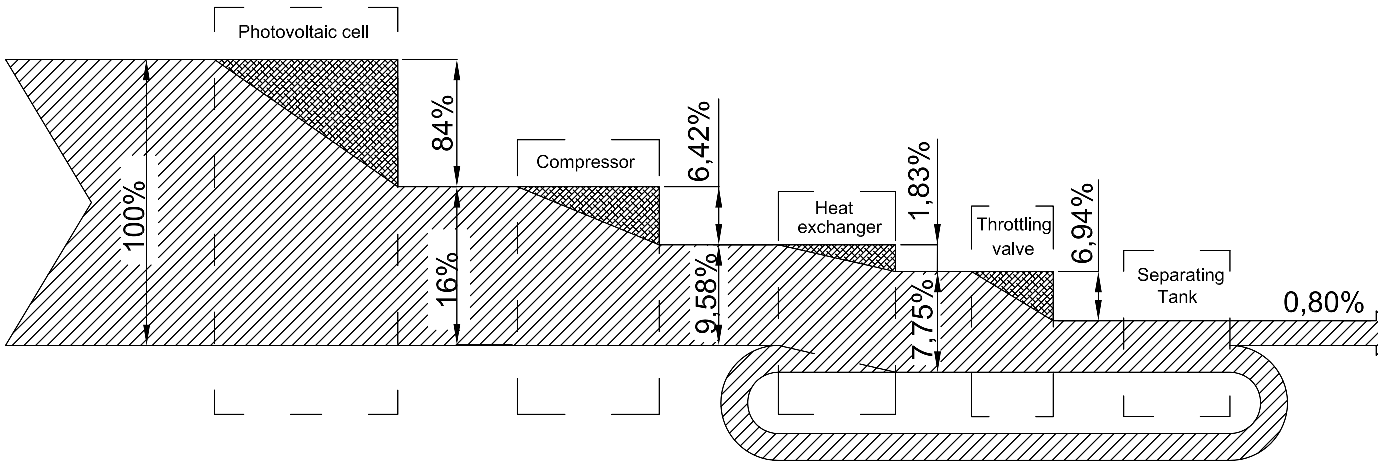

Figure 8. Grassmann diagram for storing process

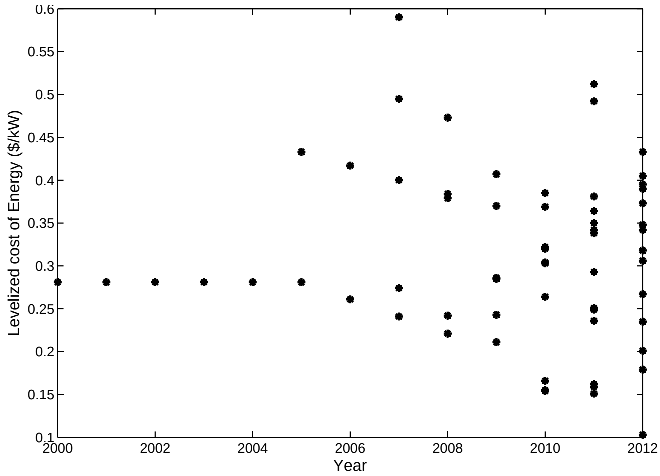

Figure 9. Levelized cost of Energy of photovoltaic cells

that require a great demand of energy, including covering demand that are bigger than the contracted capacity. According to the results, the application of this kind of system may have more utility in small residential and commercial sectors, having long-term returns. It is necessary that a larger investigation in the improvement of internal components of the generation cycle be done in order to reduce and potential losses. It is important to verify other cycles as: Collins and Claude.

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