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# Environmental and Exergetic Investigation of Low Energy Sources Organic Hybrid Heat Pumps

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# Environmental and Exergetic Investigation of Low Energy Sources Organic Hybrid Heat Pumps

RabebToujani [α] & Nahla Bouaziz [σ]

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## I. Introduction

Faced with the degradation of ecosystems and the quality of life, social and political concern for the environment has continued to grow. Economic life can no longer ignore this aspect thanks to laws, imposed standards and political initiatives.

Whatever their intentions, actors need environmental management tools to assess changes in the environment. Thus, the decisions taken in a sustainable development policy need to be designed and evaluated according to a suitable frame of reference. By going through all the environmental impacts that an activity can generate, we observe a variety of indicators to study.

Unlike the economic point of view where a single indicator, the financial cost, characterizes the impact of an activity, the environmental assessment must be based on a multi-criteria analysis. It is a combination of several impacts; it also takes into account the particular importance of each of them with regard to environmental aspects. Thus, a multicriteria analysis allows decision-makers to argue their decision by reducing the risk of a conflict situation and also seeking solutions that correspond to the best compromise for all stakeholders.

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The analysis of the performances of the various technologies leads in a traditional way to calculate their energy balances. In addition, especially when one seeks to optimize a system, the development of its exergy balance is of great interest, because this balance makes it possible to quantify irreversibilities. Drawing up an exergy balance does not pose any particular difficulty but requires to be done with great care.

The exergy provides thermodynamics with very relevant tools to be coupled with other approaches: economic, ecological, environmental, technological, etc.

As an indication, exergy analysis and economic analysis form the thermo-economic basis, which is also called exergo-economic analysis [1, 2]. Thus, an exergy loss directly implies economic losses [3, 4]. The consideration of exergy efficiency as an additional criterion for comparison with environmental criteria, through ELCA, will provide LCA with more relevant tools for accounting for the consumption of abiotic resources. Thus, the increase in the exergy efficiency of the processes was considered as a solution to reduce the environmental impacts through the reduction of the degradation of natural resources. The most important contribution of ELCA in the framework of the implementation of a sustainable development undoubtedly remains the perspective of life cycle which makes it possible to save resources and to solve the pollution problems in a definitive way, avoiding thus moving them from one point in the production chain to another.

The choice of the field of refrigeration may seem reductive, in fact, a proven technology exists: absorption. These performances can also be considered as resulting from a natural optimization, resulting from know-how acquired over several decades of research, and responding to current technical and economic constraints. This technology can therefore serve as a test for the various thermodynamic criteria which will be defined below.

Absorption machines have several advantages such as environmental protection. In addition, this type of refrigeration machinery does not use CFCs (chlorofluorocarbons) which deplete the ozone layer, Kang et al. [5], Boer et al. [6], Göktun [7], Laouir et al. [8]. They are possibly silent compared to vapor compression machines, Riffat and Guoquan [9].

A recent study [10], combines a conventional vapor compression refrigeration system with an absorption refrigeration machine. Indeed, this system has the advantages of both processes, which results in a more profitable system. Electricity / thermal consumption is considerably reduced.

The results obtained show that the value of the coefficient of performance is greater than that of a system operating in stand-alone mode. From another perspective, R. Haghbakhsh [11] investigated the feasibility of using DES absorbents (Reline, Ethaline or Glyceline) as an operating fluid in absorption refrigeration cycles further analysis was performed to assess thermodynamic properties and determine optimal operating conditions.

The results indicate that these ESD / water working fluids can be adapted to absorption refrigeration cycles although their energy efficiency appears to be relatively low.

Based on an exergetic approach, a study of a new combined cycle power plant assisted by high temperature solar energy was proposed by F.Calise [12].

It is a high temperature solar cooling system coupled with a conventional combined cycle; the aim being to improve the efficiency of the system and the electrical capacity.

The system is analyzed from an exergy point of view, on the basis of an energy-economic model for which the efficiency is higher compared to that of a conventional model.

The results showed that the components of the Joule cycle (combustion chamber, turbine and compressor) are the main sources of irreversibility.

The optimization of the double and triple effect cycles, resulting from research carried out in the laboratory, has enabled the design of high-performance installations, which are now on the market. Note that the cycles implemented today result from a thermodynamic analysis including the second principle.

The analysis of absorption cycles has been developed from an energetic as well as an exergetic point of view. The latter is based on the notion of exergy destruction and therefore the degradation of the quality of energy transformations taking place within the components of an installation.

Two types of absorption / compression cycles have been selected. [13, 14] The first is single-acting, the results of the latter are compared to the conventional absorption machine. The results of the second double-acting configuration were also compared with those of the conventional double-acting absorption machine. In terms of performance, the single-stage hybrid machine offers relatively greater results when compared to the double-stage one [15].

In another approach, the integration of other organic absorbent / refrigerant pairs is envisaged, in order to further optimize the exergy and energy performance of the machine [16].

The most common refrigerant mixtures are water and lithium bromide mixtures, water being the refrigerant and lithium bromide the solvent and the mixture of ammonia and water in which ammonia is the fluid. refrigerant and water the solvent. A certain number of characteristics required of the fluids used in compression machines can be transposed to absorption machines. In particular: high enthalpy of vaporization, Non-toxicity, Low viscosity, High thermal conductivity, A moderate cost.

Recently, research has focused on the study of new refrigerant / absorbent pairs that can be an excellent alternative to conventional pairs. Wang et al [17], in 2011, presented a study of a diffusion absorption refrigeration (DAR) system operating with the R23 / R134a couple as refrigerants and DMF (N, N-dimethylmethanamide) as absorbent, it These torques have been proven to be a solution for the use of low energy sources.

A study, carried out by Ben Ezzine et al in 2010 [18] shows that the R124 / DAMC couple provides a higher COP than that of ammonia / water and that it presents an intercurrence for solar refrigeration. An experimental study prior to the latter two, in 2008 carried out by Muthu et al [19], shows that the COP of a refrigeration system using the R134a / DMAC couple reaches 45% under the test conditions and that this couple can be also used for low energy sources.

It is customary to evaluate the efficiency of energy transformations by calculating the energy yield, in fact, according to the first principle of thermodynamics, for each process, energy is conserved. It can neither be destroyed nor produced. In contrast, the exergy approach, as determined as the energy method, results from the second principle of thermodynamics, and focuses on the degradation of energy during a process. Exergy potentially presents a powerful tool that is used to carefully assess the quality of the flows involved in a well-defined process. The resulting analysis can be used as a benchmark in optimizing energy systems [20]. This analysis also makes it possible to identify areas of failure in a process in order to design new systems contributing to sustainable development [21]. Different indicators resulting from exergy analysis have been supported by [22] to assess the sustainability of an energy process within the framework of industrial ecology. These parameters take into account exergy efficiency and environmental efficiency.

Indeed, different methods have been proposed for the energy evaluation of the performance of anthropogenic systems. The motivation for these studies was mainly rooted in the economic industry, but there were implicit and explicit environmental concerns permeating.

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The inability of standard exergy analysis to determine the best configurations when monetary costs have been approached, in the field of process analysis, by: a theory of common economics and thermodynamics, correctly termed thermo-economics, developed to industry standards over the past ten years or so on the basis of formulations. In this approach, the yields are calculated via an exergy analysis, and the non-energy costs (capital, interest, overheads, labor, maintenance, insurance, etc.) are linked to the technical and thermodynamic parameters of the process considered.

One of the objectives of EEA (Extended exergy accounting) is to go beyond thermo-economics and to develop a formally complete theory of costs based either on an exergy or monetary metric, that is to say a general pricing method in which kJ / kg or kJ / kW are perfectly and systematically equivalent to € / kg and € / kW, respectively).

The first extrapolations of exergy in the context of sustainable development focused on the valuation of natural resources and process waste (Belhani, 2008) [23]. The basic idea is to minimize the irreversibilities related to non-renewable resources. The exergy also brings a good clarification which identifies two primordial criteria, the quality and the degradation of the energy;

Life Cycle Analysis is concerned with the environmental impacts generated throughout the product life cycle. However, the objective is to go beyond taking the environment into account and provide practical recommendations on the integration of social and economic dimensions in decision-making, from a life cycle perspective [24]. Consequently, the life cycle analysis becomes a step in a more comprehensive approach to sustainable development and not an objective in itself. According to Grisel and Osset [25], life cycle management aims to improve the environmental performance of an industrial sector through eco-design. The eco-design or control of the environmental impacts of a product is based, at best, on its Life Cycle Analysis (LCA) [26]. Eco-design appears as a process of integrating environmental aspects into the design and development of products, the objective of which is to reduce the environmental impacts of products throughout their life cycle. Thus, eco-design appears as a solution so that companies can integrate the priorities of individuals with regard to sustainable development into commercial interrelationships [27]. Breset and Van Hemel defined eco-design as a sustainable solution which consists in finding the perfect balance between ecological and economic requirements in product development.

Eco-design integrates environmental considerations into product life cycle reasoning. To be more precise, this concept means reducing from design the impacts in economic, social and environmental terms, and maximizing the concept of sustainable development over all stages of a product's life cycle. By adopting an eco-design approach, companies can develop products that are more respectful of the environment while maintaining the objectives of competitiveness, quality and time to market. Therefore, LCA aims to enable companies that use it to improve their performance from an eco-efficiency perspective. This is a concept that was revealed at the Rio conference in 1992. According to the WBCSD (World Business Council for Sustainable Development), it is about providing goods and services at competitive prices that meet the needs. human beings and improve the quality of life while gradually reducing ecological impacts and resource consumption throughout their life cycle.

Cornelissen redefined the concept of sustainable development, incorporating the notion of exergy, as follows: “for sustainable development, the destruction of the exergy reservoirs of natural resources must be minimized to a level at which there is no no damage to the environment and to which the supply of exergy to future generations is secured”.

Indeed, exergy and LCA can be used for sustainable development. The methodology which brings together these two tools in a single composition called Exergy Life Cycle Analysis. Indeed, it will take advantage of the strong bridges separated from each approach for the establishment of sustainable development on the one hand.

Exergy is reputed to be an effective means in the political decision-making of energy strategies as it is the only function which harmonizes energy, environment, economy and sustainable development [28]. The classic definition of "nothing is created, nothing is lost, everything is transformed", with the exception of nuclear reactions, makes the concept of the depletion of materials and non-renewable energies subjective.

On the other hand, the consumption of resources is also a form of damage to the environment; a resource is a substance, an ordered state, out of balance with the environment, therefore having a high exergy value; the consumption of a resource therefore reflects a loss of exergy value.

Lombardi [29] rethinks that exergy efficiency is an additional element of review to the environmental criteria used in the methodological framework of LCA, because exergy cannot replace the impact assessment methods of the methodological framework of LCA.

Exergy can be utilized by combining with ACV at three levels:

- Simultaneously with LCA for inventory accounting and as a criterion for the depletion of natural resources, thus constituting an additional criterion judging the effectiveness of the scenarios studied;

- A pre-selection criterion, judging the effectiveness of the scenarios studied before being analyzed by a full LCA;
- A post-selection criterion, judging the effectiveness of the scenarios studied beforehand by a complete LCA.

However, improving the exergy efficiency of processes is revered as a way to reduce environmental impacts through reducing degradation of natural resources. The objective of this study is to carry out a comprehensive analysis of the life cycle of a cooling system from renewable energy sources, presenting its consequences on the environment.

## II. System Presentation

In this paper, we propose to study a hybrid compression/absorption heat pump for which we have introduced new refrigerants chosen for their environmental characteristics and which allow the system to be adapted to a source with low enthalpy value.

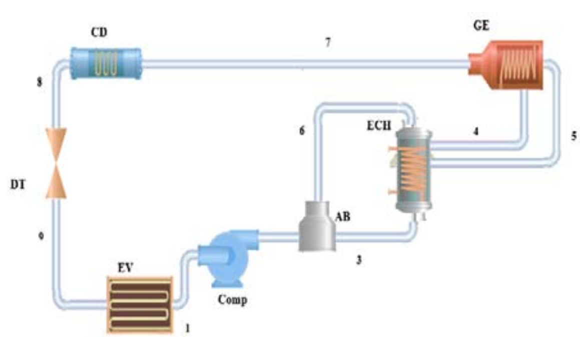


*Fig. 1:* Hybrid heat pump

The heat pump (figure 2), subject of this study, is a combination of the conventional absorption pump and the compression pump. A compressor is injected into the cycle, upstream of the absorption part, in order to improve the absorption process. The system operates at three pressure levels: the refrigerant vapor leaving the evaporator (1) is at the lowest pressure (PEV). It is compressed by an isentropic transformation (2) into an intermediate pressure (P2) and finally injected into the absorber. The rich solution from the absorber (3) is heated by the lean solution from the bottom of the generator (5) by a solution heat exchanger. The condenser and the generator operate at the third pressure level (PCD) which is the condensing pressure.

Numerical analysis was performed using Aspen plus software. The thermodynamic properties of binary mixtures were determined using the NRTL model based on experimental results. When it is necessary to choose a working fluid for an application, it is generally desired that it lead to high energy performance and that it be suited to the operating conditions of the cycle.

A certain number of characteristics required of the fluids used in compression machines can be transposed to absorption machines. The criterion of non-toxicity is essential, the fluid must be non-flammable, non-explosive, non-corrosive, and has no dangerous physiological action.

Some researchers have focused on new refrigerant / organic absorbent pairs that can be a good alternative to classic pairs.

The configuration proposed represents an improved cold production system for which a new organic pair R245fa / DMAC (1,1,1,3,3-Pentafluoropropane / N, N-dimethylacetamide) has been integrated. This family of refrigerants is characterized by a low global warming potential (GWP).

The results showed that the new configuration has the same energy performance as that of the conventional system. The optimum COP is around 45% for R245fa / DMAC, however, the same value is obtained for a conventional system where the operating pressure is in the order of 600kPa. In addition, the added value lies in the adaptation of the machine to organic mixtures which have a relatively low temperature and between 60 ° C and 80 ° C, which allows the use of energy sources with low energy value. The exergy analysis also revealed a decrease in the irreversibility of the system.

In reality, the use of such refrigerants allows the installation to be adapted to a low energy source.

## III. Exergetic Analysis

The exergy balance is based on the exergy destruction method, it is calculated for each component as follows [30]:

$$ExDi = \sum (\dot{m}\,Ex)_{in} - \sum (\dot{m}\,Ex)_{out} \pm \sum (Ex_{\dot{Q}}) \pm \sum \dot{W} \quad (1)$$

The first two terms represent the exergy of the flows entering and leaving the control volume.

The third and fourth terms are the exergy associated with the heat transfer $\dot{Q}$ of the source maintained at a constant temperature T and equal to the work obtained by the Carnot engine operating between T and T0, and is therefore equal to the maximum reversible work that can be obtained from thermal energy Q. The last term is the mechanical work transferred to or from the control volume.

$Ex_Q$ is the thermal exergy and is expressed as follows [31, 32]:

$$Ex_Q = \dot{Q}(1 - {}^{T_0}/_{T}) \quad (2)$$

We can also express the loss of exergy in terms of exergy efficiency; it is the rate between the exergy of entry and that of exit [33]:

$$\eta_{ex} = \frac{outlet\ system\ exergy}{intletsyst\grave{e}meexergy} \quad (3)$$

Several hypotheses were taken into account in the exergy study:

- Kinetic and potential exergy is neglected.
- All transformations are in a stable state.
- Pressure and heat losses in the system component are neglected.
- The exchange temperature is the logarithmic mean temperature of the inlet and outlet.
- The reference temperature and pressure P0 and T0 are respectively 1atm and 25 ° C.

## IV. Environmental Analysis

The sum of the exergy destruction gives the irreversibility of the life cycle of the system and therefore the impact indicator of the depletion of natural resources.

Exergy analysis is a focused approach and it does not take into account the exergy developed throughout the production chain.

It is in this sense that the Analysis of cumulative exergy consumption (CExC).

Indeed, this method is used to assess the exergy of all-natural resources consumed in a process.

It takes stock of the quality of the resources and it is expressed as follows:

$$CExC = \sum_{i}^{N} Ex_{r,i} \tag{4}$$

With: $Ex_{r,i}$ the exergy of natural resource i which is part of the process and N is the number of natural resources.

This approach has been applied for different industrial processes [34].

CExC analysis is based on the same principle of LCA where all the elements involved in the process are taken into account.

In fact, the notion of exergy has been exploited in the context of life cycle analysis as an alternative to methods of measuring the depletion of natural resources [35].

Likewise, the added value in relation to sustainable development is to reduce irreversibilities due to the use of non-renewable resources.

Improving exergy efficiency imperatively leads to a reduction in environmental impacts.

In the same context, efforts have been made to oust the multicriteria side of the LCA environmental study by a single quantity which is exergy.

Indeed, it was introduced in the LCA methodology to be used as a uniform indicator of the total environmental impact [36].

It is approved as a unit of measure for the potential of a pollutant to cause environmental degradation [37].This will allow us to minimize the amount of data with a single magnitude that clarifies vision without resorting to parameters used in conventional LCA and which are deemed to be subjective;

*a) Solar source*

From the perspective of producing energy more economically, the ability to limit wastage rates is a major issue. The proposed new model uses the principle of cogeneration, already applied in some thermal power plants, and which consists in producing both electricity and heat from the same primary source.

In the case of solar cogeneration, this involves combining, in a single module, conventional photovoltaic solar cells and a waste heat recovery system. The main objective is to improve the performance of the machine while preserving the environment. The originality of the project is based on the addition of a photovoltaic system to serve the compressor.

In addition, the use of the heat released by the photovoltaic cells will heat the coolant in order to improve the operation of the generator. This concept offers a relatively high production of electricity and heat on the same surface and improves the efficiency of these panels, which decreases with increasing temperature. For the modeling of the improved heat pump, the work was carried out for a condensing temperature equal to 40 ° C, the temperature of the generator in fact varies according to the daily solar radiation.

He basic function of the photovoltaic installations analyzed in the context of this work is the production of electricity.

The functional unit of the LCA should be determined in correspondence with the function of the observed system and serves as a basis of comparison for the analysis of the results of different photovoltaic power generation systems.

The environmental impact assessment stage translates elementary flows into environmental impacts. It includes classification of emissions by impact category, intermediate characterization and damage characterization. The indicators selected in this work include environmental impact indicators and energy flow indicators, namely:

- Global warming potential at 100 years (GWP100) in kg CO2 equivalent.
- Consumption of renewable primary energy in MJ.
- Consumption of non-renewable primary energy in MJ.
- The environmental assessment of the PV system is based on three different stages:
- Generation of impact factors on PV systems to estimate the environmental impacts of the PV system.

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- Evaluation of the productive life cycle of the photovoltaic installation on the prospective site and on the reference site (reference sunshine).
- -Voluntary environmental effects of the PV system reported to the UF functional unit.

Two types of results are expected for the environmental impacts: the environmental impacts linked to the producible estimated on the anticipated site of the installation and the so-called reference environment.

To calculate these impact factors, two steps are necessary:

The first step is to calculate the impact factors per process such as:

$$Imp_n = FI_n . QR \tag{5}$$

The impacts of each of the processes are calculated according to equation (5) and then added to obtain the impacts corresponding to each PV subsystem (PV infrastructure, additional infrastructure, site, maintenance). The impacts of the PV system are finally obtained by summing the impacts of each PV subsystem.

At the end of the first step, the impacts of the PV system on its life cycle are defined to calculate the environmental impacts by the power of the PV system:

$$Imp_{sysPV\,(KWc)} = \frac{Imp_{system\ \ pv}}{Puiss_{nom}} \tag{6}$$

The PV impact factor (kWp) corresponds to the environmental impacts of the photovoltaic installation per nominal power.

To assess the producible, we opt for a simplified method allowing component manufacturers to have a reference calculation to estimate production and thus serve as a basis for comparison for different products.

To estimate the production potential over the life cycle of the PV system, Equation (7) is used:

$$E_{total} = \sum_{n=0}^{lifetime\ \ of\ \ the\,modules\ \sum\frac{100-\partial.n}{100}} \left(\frac{P_c . Ir_{plan} . Pr_{instal}}{\phi_{irrSTC}}\right. \tag{7}$$

The degradation of the modules reduces the efficiency of the photovoltaic system during the lifetime. A linear degradation of 0.7% per year must be considered, which corresponds to a total degradation of 20% at the end of the life of the modules.
A 30-year module life should be considered.

The value of the coefficient of performance of a PV system, which is a correction factor for the overall efficiency of the photovoltaic installation, depends on:

- DC / AC conversion system
- Actual operating temperature of the modules
- Type of module integration

The following equation is used to assess the environmental impacts of the PV system based on the functional unit:

$$Imp_{UF} = \frac{Imp_{system\ \ pv}}{E_{total}} \tag{8}$$

Impacts by functional unit must be calculated for each impact category chosen.

*b) Wind source*

The life cycle stage responsible for the majority of the impact for the two wind energy sectors is the manufacture of components, using mainly fossil energy.

In order to carry out the LCA of a product, it is essential to define its function. In our case, the functional unit chosen for this LCA is as follows:"1 kilowatt-hour, from wind power production capacity, delivered to the electricity grid, for a lifespan of 20 years" State-of-the-art environmental assessments report that the majority of studies consider a system life of 20 years (Arvesen, 2012).

An average load factor is used in order to be as representative as possible over the lifetime of the installation. The environmental impact assessment step translates elementary flows into environmental impacts. It includes the classification of emissions according to impact categories.

It makes it possible to detect the main contributors to the impact on each indicator. The phases of the life cycle are first studied in order to understand their responsibilities as a whole and then to specify which processes and substances are responsible for the impact.

*c) Biomass source*

This part is devoted to the LCA of a biomass recovery system, namely forest residues.

The UF chosen for this study is a ton of biomass that feeds our system. This UF is generally chosen by studies aiming to recover agricultural and forestry waste [38].

The structure of the project consists of subdividing the system into a set of elementary modules [39].

The application of life cycle analysis in the bio-resources sector reveals specific issues.

Until now, the questions asked to the specific problems of LCA applied to products of biomass origin have not all been answered and the answers that have been provided have not been the subject of a consensus. Real at the level of the LCA community.

From the extraction of their raw material to their end of life, biomass products are the source of various carbon-biomass flows.

## V. Results and Discussions

The objective of this investigation is to analyze the different models, so management and life cycle thinking are very important.

The best solution must have the lowest environmental impacts; this exergetic methodology makes it possible to evaluate the scenarios considered and to achieve this objective.

*a) Solar heat pump*

In figure 2, we can see the contribution of each stage of the life cycle on the indicator of global warming for solar configuration. The stage mainly responsible for the impact is the construction phase with a contribution of 88%

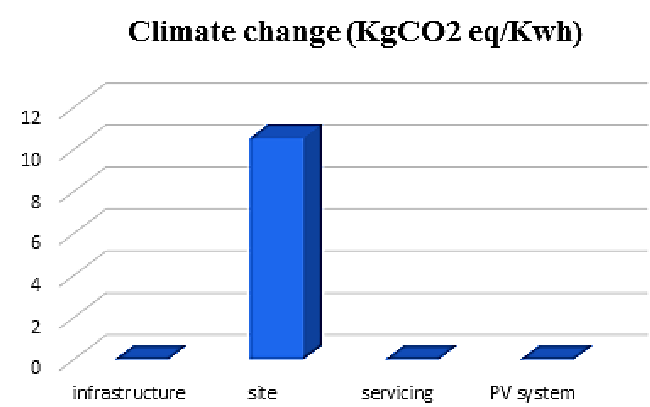


*Fig. 2:* Climate change (KgCO2eq/Kwh).

In the following Figure 3, we can see the contribution of each stage of the life cycle on the indicator of Ozone Layer Depletion. Mainly, the element responsible for the impact is the PV system with a contribution of 90%.

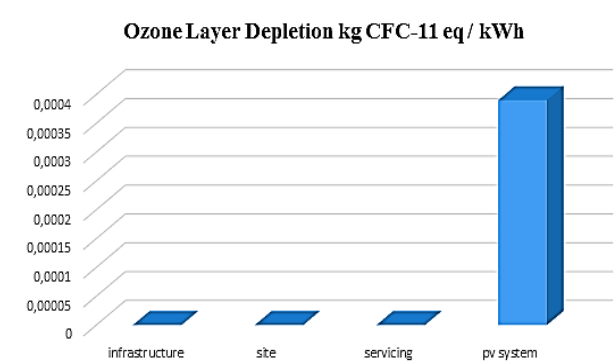


*Fig. 3:* Ozone Layer Depletion kg CFC-11 eq / kWh

For renewable primary energy consumption (figure 4), the contribution of each stage of the life cycle is also assessed. Essentially, the element responsible for the impact is the site.

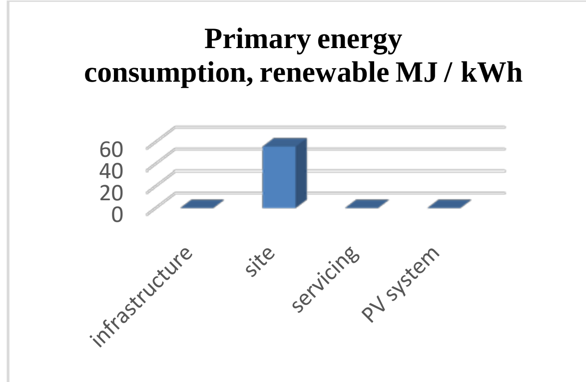


*Fig.4:* Primary energy consumption, renewable MJ / kWh

The following figure 5 shows the contribution of each indicator to the system life cycle.

Obviously, that of non-renewable primary energy consumption has the most important contribution.

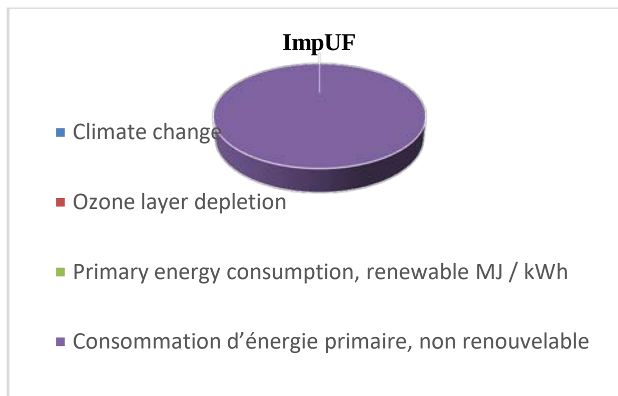


*Fig. 5:* ImpUF

The indicators that result from the exergy methodology are irreversibility and CexC. They have been evaluated in the installation and shown in the following figure 6.

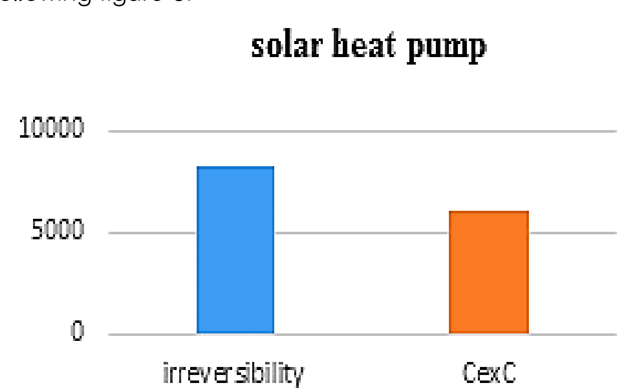


*Fig. 6:* Exergy impact of the solar heat pump

In the following figure 7, we can see the contribution of each stage of the life cycle on the acidification indicator. Primarily, the stage responsible for the impact is the manufacturing phase with a 60% contribution including an avoided impact of 22% through end of life.

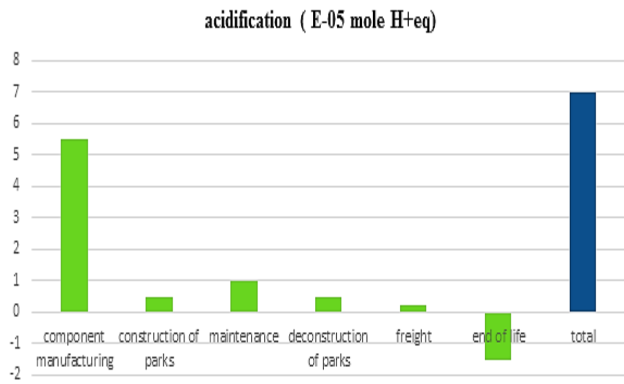


*Fig. 7:* Environmental impacts of 1 kWh on the acidification indicator

*b) Improved cycle using wind energy*

Global warming is dominated by the construction of the various components with a larger share of the nacelles.

The main sources of impact related to the manufacture are for the rotors the composition of the blades, the amount of steel in the nacelles and in the masts, and finally the manufacture of clinker in the concrete of the foundations. These materials emit CO2 primarily because of the energy they consume to be produced.

In figure 8, we can see the contribution of each stage of the life cycle on the indicator of global warming. The step primarily responsible for the impact is the manufacturing phase with a 66% contribution including an avoided impact of 23% through end of life.

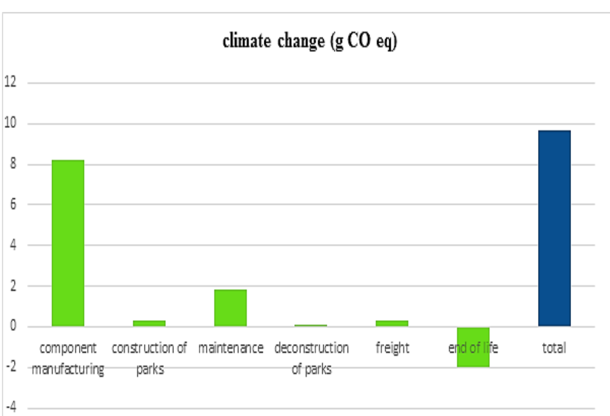


*Fig. 8:* Environmental impacts of 1 kWh on the global warming indicator

The steel industry is considered to be a major emitter of greenhouse gases, with up to two tonnes of CO2 emitted for one tonne of steel produced. These emissions are mainly linked to the energy used in the various transformation processes.

The impact of the rotors is entirely related to the use of epoxy reinforced fiberglass, the production process of which requires a great deal of energy.

The impact of the operation and maintenance phase is linked to the transport of maintenance workers because of the CO2 emitted directly by the technicians' vans.

The total contribution of the construction and deconstruction parts of the fleets is linked to the quantity of fuel used in construction machinery. Freight has little impact on this indicator despite a type of truck transport.

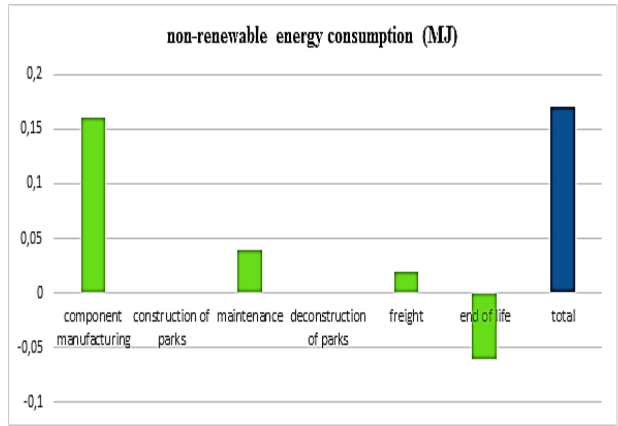


*Fig. 9:* Environmental impacts of 1 kWh on the CED indicator (non-renewable)

In Figure 9, we can see the contribution of each stage of the life cycle on the indicator of CED NR. The step primarily responsible for the impact is the manufacturing phase with a 64% contribution including an avoided impact of 29% through end of life.

In general terms, the substances responsible for the impact are the main types of non-renewable resources used for energy production: oil, gas, coal and uranium. These impacts are mainly related to the production of steel for masts and nacelles as well as plastic / epoxy fibers for blades and nacelles.

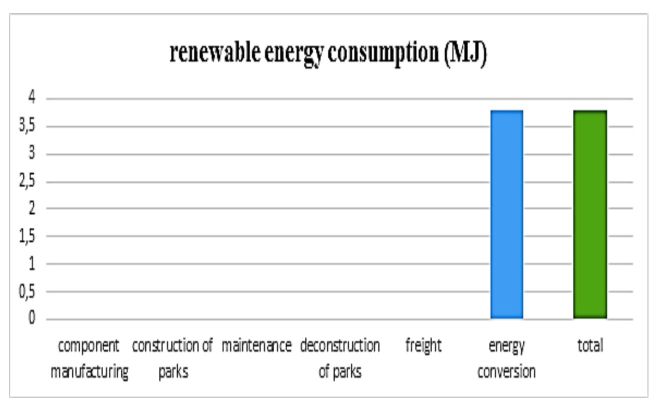


*Fig. 10:* Environmental impacts of 1 kWh on the CED indicator (renewable)

In Figure 10, we can see the contribution of each life cycle stage on the indicator of CED R. The stage mainly responsible for the impact is the conversion of kinetic energy using wind power. In fact, we are studying the impact of 1 kWh from the wind power sector, it is logical to find this kilowatt hour in the demand for non-renewable energy.

In addition to the environmental impacts presented above, the figure 11 shown below shows the two ecological indicators that result from the exergy analysis, namely, the irreversibility and the CexC assessed in the installation.

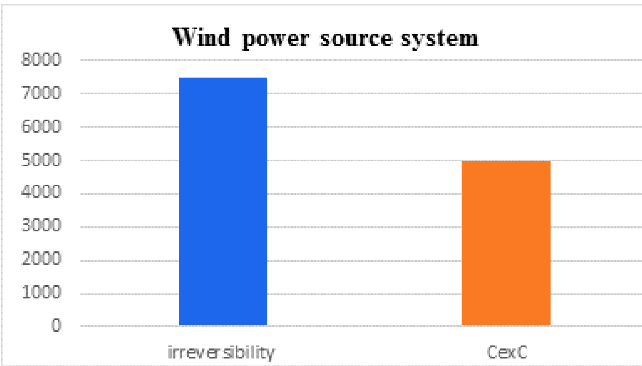


*Fig. 11:* Exergy impact of the wind heat pump

c) *Improved hybrid heat pump coupled to a biomass power plant*

The biomass carbon balance is not always zero. In the case of the landfill scenario, the degradation being slow and incomplete, at the end of its life, all the biomass carbon is not enlarged. One of the simplifying methodological choices adopted with regard to the consideration of flows linked to biomass carbon is to make the hypothesis of neutrality, on the basis that the fixed carbon is enlarged during the product's life cycle.

The methodological choice of not taking into account the flows linked to biomass carbon does not make it possible to assess the negative or positive impact of these flows. For example, it puts a cut and burnt forest and a sustainably managed forest at the same level. On the contrary, taking into account biomass carbon will make it possible to differentiate an exotic wood product from sustainably managed forests from a product resulting from deforestation which cannot claim $CO_2$ removal. Likewise, this methodological choice does not make it possible to account for the improvement in the energy efficiency of biomass boilers.

Thus, the climate change indicator may turn out to be negative, reflecting a beneficial effect in the fight against climate change, if the biomass carbon is not fully expanded during its life cycle and if it offsets the GHG emissions of 'fossil origin. This will be all the more true as biomass carbon will be permanently stored, that is to say beyond 100 years.

Evaluating the environmental impact of a product, essential for decision support in the context of progress initiatives, is a difficult and complex subject to deal with, encompassing many parameters and affecting multiple criteria.

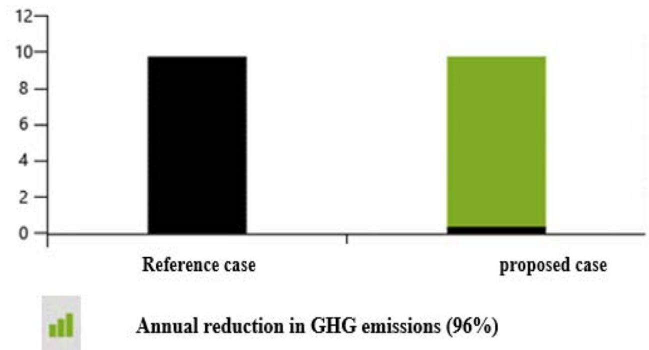


*Fig. 12:* Annual reduction in GHG emissions

In addition to the environmental impacts presented above, the figure 13 illustrated below represents the two ecological indicators that result from the exergy analysis, namely, the irreversibility and the CexC assessed in the installation.

## VI. General Conclusions

At a time of awareness of the finitude of resources and the growing need for energy, the concept of sustainable development must take a central place in the evolution of society. To achieve this goal, it is now recognized that a profound change in consumption is needed; whether it is energy consumption or finished products. We believe that this paradigm shift is only possible if all actors move forward in concert on the various issues we are facing. Everyone at their own level must therefore be able to make the decisions that are binding on everyone. This is the logic that motivated the study of this thesis, we are studying the possibility of a sustainable cold production solution.

Reducing energy needs and $CO_2$ emissions is of major interest in the general context of rising energy prices and ecological demands.

Traditional approaches to energy optimization often focus on improving the efficiency of individual equipment, or that of energy infrastructure. This is where the energy integration of processes comes into play, with the objective of optimizing processes from a global perspective.

Exergy Analysis itself is a valuable tool in energy integration. Within the imposed framework of minimizing total annual costs, entropy analysis helps determine the optimal plant concept, optimize energy conversion and use, and improve profitability.

It is an original contribution concerning the impact on the environment of all anthropogenic activities and showing that exegetical efficiency constitutes a fundamental criterion for the preservation of the environment.

The objective of this work is to study cold production scenarios in order to determine which is the most eco-efficient.

This study was eventually expanded. The results obtained confirmed the possibility of adapting the heat pump to a renewable energy source. In our case, we opted for three types of sources: solar, wind and biomass.

The results can be seen as tools to help define new energy and environmental policies.

The consideration of exergy efficiency as an additional comparison criterion to environmental criteria, through the Exergy Life Cycle Analysis, will endow Life Cycle Analysis with more relevant tools for accounting for the consumption of abiotic resources. Thus, the increase in the exergy efficiency of the processes was considered as a solution to reduce the environmental impacts through the reduction of the degradation of natural resources. As a result, ELCA was retained in this work as a tool for comparing cold production scenarios. It has provided us with relevant tools for comparison between the different stages of the models proposed by identifying areas of potential for environmental improvement.

*Nomenclature*

P = Pressure (bar, Pa)
T = Temperature (K, ° C)
x = Mass fraction
ExD = Destruction of exergy.
$\dot{m}$ = mass flow (kg.s-1)
$W$ = Power (W)
$Q$ = heat exchanged flow (W)
$Ex$ = Specific exergy of a flow (kJ.kg-1)
ηex = Exergy efficiency
Impn: Impact of process n
FIn: conservative impact factor
QR: reference quantity
ETotal: value of the producible
Pc: maximum power of the photovoltaic installation (expressed in kWp)
Ir: average annual irradiation in terms of installation
Main: Performance ratio or coefficient of performance of the photovoltaic system: illumination under STC conditions (equivalent to 1 kWp / m$^2$)
δ: Annual degradation of modules
n: Service life of the modules (expressed in years)
ImpUF: Impact of the PV system per functional unit
ImpSystem PV: Impact of PV system
ETotal: value of the producible

*Subscribed*

i = Component or stage i
T = Total
0 = Reference
EV = Evaporator
COMP = Compressor
GE = Generator
ECH = Solution exchanger
AB = Absorber.
V = Steam

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