Study of Magnetic Energy transition to thermal effect by Renewable Energy

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Abstract: Magnetic heating, refrigeration and energy conversion have been stated so vital challenges for ecofriendly forthcoming choices. Recent case studies are focused attention on novice thermo magnetic systems, devices functioning through thermo magnetic effect, run by renewable sources. The aim of this work is a case study presentation of new thermomagnetic energy prototype coupled with renewable technologies or industrial waste heat. The paper is sected into four parts: the first gives a general state of art about magneto-caloric energy transition systems, the second explain all common thermodynamics and magnetic laws controlling the process, the third and fourth sections study in more detail the case study presented.

Keywords — Renewable energy, Magnetism, Motor, Thermo magnetic effect.

I. INTRODUCTION

Today, around 33 % of the power consumed in Europe countries is used for solace in buildings (heating, air cooling and air exchange). As far as energy consumption of buildings [1] is considered, the various initiatives have primarily concentrated on the development of renewable energies [2] and to the diminution of energy necessities like the building energy efficiency certification. However in the short term, good results can be achieved by the adoption of renewable energy consumption systems.

As regards on emission of engines, the pressure is on manufacturers. First of all, conventional refrigerants such as HFCs were classified as greenhouse gases from 1998 Kyoto protocol on Climate Change. In a European context, the implementation of the European Union's WEEE (Waste Electrical and Electronic Equipment) and RoHS (Restrictions on the Use of Certain Hazardous Substances) Directives suggested to reduce the cooling engine emissions to increase the life span.

Recent research cases concentrate on new magneto-thermic systems run with the help of renewable sources. From this, it is possible to recognize magnetic heat pumps, magnetic refrigerators and thermo magnetic power transition machines to produce mechanical and electrical energy.

Usually we define magneto caloric refrigerators as the devices that work on magneto caloric effect (MCE), a physical phenomenon based on the effect caused by a magnetic field on the materials that bear the property of varying the magnetic entropy, as well as its temperature, when varying the magnetic field [4].

After the disastrous effect of greenhouse effect of HFCs, refrigeration systems based on the magneto caloric principle are developed and they present some advantages as:

- Energy savings up to 50% as the permanent magnets don't need electrical energy to operate;
- Reduction of greenhouse gases, the magnetic refrigeration system does not use any refrigerant gas;
- Less running cost;
- Reduction of dissonance and trembling.

Another innovative proposal based on the thermo magnetic effect is the design of thermo magnetic motors that functions based on renewable resources. These motors can transit heat into mechanical energy using the ferromagnetic materials at temperatures around the Curie point.

In general, the motor design depends on two basic parameters: the temperature difference between source and sink and the magnetic materials used.

As for the materials, French and Swiss physicists *Weiss* and *Piccard* [5] mentioned few specific properties in the XIX century. Furthermore, the use of suitable thermo magnetic materials is the most crucial these devices. Effectively, Kitanovski et al. [6] established some favorable properties as:

- suitable Curie temperature of the material;
- the relevance of the thermo magnetic with low hysteresis;

- high thermal conductivity and electrical resistivity;
- good manufacturing properties

The most common magneto-caloric materials are gadolinium and its alloys. Gadolinium (Gd) is a pure element that has good properties near atmospheric conditions. Its drawback is that it is not economical. In fact, innovative researches have studied the discovery of new cheaper materials, which are a perfect replacement of a pure material as Gd[7].

The most important parameter is the identifying the working temperature of the thermo magnetic motor that is connected to the chosen source and sink. Usually the sink is at the room temperature (22ºC), while source can be opted among different renewable sources like solar power generation, geothermal systems, waste heat from industry or garbage plant. [10], [11]will be presented by wind and solar photovoltaic system. Furthermore, the report underlines the commitment of energy saving systems for domiciliary and manufacturing sector.

In fact, the main purpose of the exploration presented is a description of a new structure that can use heat or energy losses to discourse for thermomagnetic transformation devices. In detail, the idea is an exploitation of heat (produced from renewable sources or industrial waste) that is the driven force for a latest thermomagnetic motor archetype established in Federal University of São Paulo (UNIFESP) [12]. The next sections will talk: the first about the renewable energy systems or industrial heat losses considered the force driven of our system suggested while the second chapter will denote the thermomagnetic motor pattern developed at UNIFESP.

II. THEORY

Firstly, it's fundamental to understand all the equations that explain magnetocaloric systems but more attention is required for the thermomagnetic motor. These processes work with the heat absorption from heat source and the temperature difference of the thermomagnetic material cause the entrance and exit of the magnetic field. The first law of thermodynamics is:

$$dU=dQ-dW \qquad (1)$$

where U is the internal energy, Q is heat and W represents the work. If we consider the reversible process, defined boundary conditions, a thermodynamically closed system, the Eq. 1 can be written:

$$dU=TdS-PdV \qquad (2)$$

where the symbol S identifies the specific entropy, P__ is the magnetic permeability of vacuum, H is the magnetic field intensity and M is magnetization.

Specifically for the thermomagnetic motor, we consider mathematical model presented by Trapanese [8] who states to estimate the concerts of a motor from its geometrical, magnetic, and thermal properties. This approach indicates that the thermomagnetic Curie motor is equivalent from a magnetic point of view to a dc electric machine. In the dQ theory, Trapanese used dynamic equations, under the hypothesis of a constant excitation field, and his approach reads as follows:

A. Renewable Energy systems and waste heat resources

Normally the use of renewable energies for the generation of heat energy in industries, agricultural installations and even in offices and residential buildings is, nowadays, a reality. Presently, the existing technology allows the use of renewable energy with the highest energy efficiency and in the best probable conditions regarding the safety of use and the reliability.

The renewable energy sources those can generate thermal energy include biomass and biogas, the sun and geothermal energy. However, fossil fuels give a huge contribution in the global heat production. Figure.1 shows the total heat production from various energy processes.

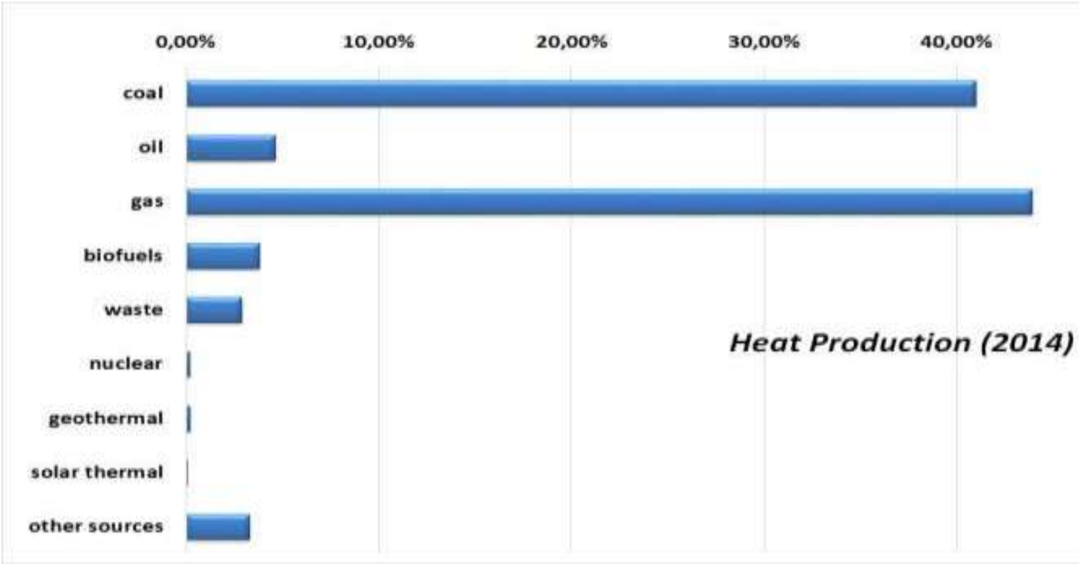

Fig.1. Total heat production by energy systems for year 2014 (data from IEA statistics)

Φ = k Id = const C = M dq I dI ……. (3)

Vq = Rq Iq + ω M dq Id …… (4)

The physical meaning of the electrical quantities used in Eqs. (3-4) has been clarified in [8].

III. RENEWABLE ENERGY SYSTEM (RES) COUPLED WITH A THERMOMAGNETIC PROTOYPE

The Paris Agreement on environment change, which entered into force in November 2016, is at its heart an treaty about energy [9]. The latest IEA [9] report say that 60% of all new power generation capacity to 2040 (in their main scenario) will come from renewable and, by 2040, the majority of renewable - based generation will be competitive without any subsidies. The study recognizes that one half of electrical power

In the last years the renewable energy sources used for heating or cooling purposes have received relatively little attention compared with those used to generate electricity and produce transport fuels. This is surprising because the demand for heat consumes the largest share of primary energy supply and RES could be an interesting alternative. Figure 2 shows all renewable energy sources converted to energy carriers that are used to provide useful heating.

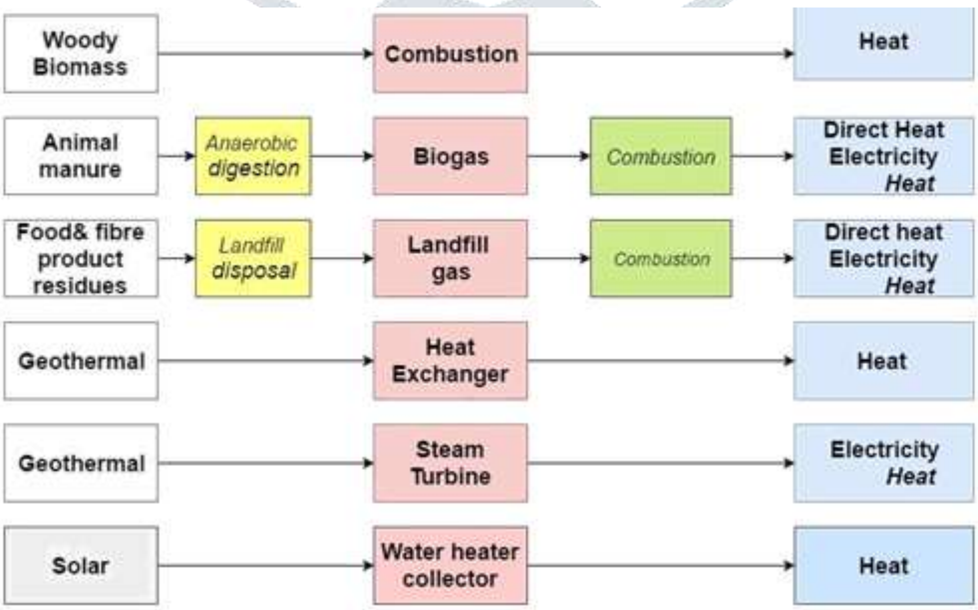

Fig. 2. Sources used as input for renewable heating

In addition to energy systems, waste heat produced from numerous industrial plants is a big reserve that sometimes can be a loss. Numerous European data indicates that industry sector uses 25% of the final energy consumption to produce it and consequently increase 20% of GHG emissions. This consequence influenced numerous investigations on an efficient energy use in industrial processes that means a more effective value of waste heat generated.

The most important sources of waste heat for most industries are exhaust and flue gases and heated air from heating systems such as high-temperature gases from burners in process heating; lower temperature gases from heat treating furnaces, dryers, and heaters; and heat from heat exchangers, cooling liquids, and gases. Table 1 presents the details of typical major waste resources.

Remark that needs identify the industrial waste heat so to develop machines that recovery this energy losses. In the section inserted below, we describe a thermo magnetic motor that can work with industrial waste heat.

TABLE I. INDUSTRIAL WASTE HEAT SOURCES DATA [13]

Sl. No	Industrial Waste Heat Sources		
	Waste Heat Source	*Temperature Range [°C]*	*Cleanliness*
1	Furnace or heating system exhaust gases	316-1,100	Varies
2	Gas (combustion) turbine exhaust gases	480-600	Clean
3	Jacket cooling water Exhaust gases (for gas fuels)	90-100	Clean
		480-600	Mostly clean
4	Hot surfaces	65-316	Clean
5	Compressor intercooler water	38-82	Clean
6	Hot products	100-1,370	Mostly Clean
7	Steam vents or leaks	120-316	Mostly Clean
8	Condensate	65-260	Clean
9	Emission control devices	65-816	Mostly Clean

B. Thermo magnetic Motor Prototype

The idea of magnetic motors is very old like the proposal made by Thomas Edison in 1888 [14] by Nikola Tesla in 1889 [15].

In Tesla's project [15], a piece of soft magnetic material is attached to a pivoted rod and attached to a spring, that is attracted by a permanent magnet. When heated above Curie temperature, it loses magnetization and is no longer attracted by the magnet, being pulled away from it by the spring. In this movement, this piece is withdrawn from the heat source, cooling and passing again through the magnetic transition, returning to be magnetic and to be attracted by the magnet, whose force of attraction surpasses that of the spring. This sequence of events yields a reciprocal movement, which can be used as a mechanical motor.

Differently, Edison's [14] device has a beam of fine iron tubes. The boiler produces hot gases that flow through a part of the tubes, heating them above the Curie temperature, which causes them losing the magnetism, and thus they will not be attracted to the magnet poles anymore. The magnet encompasses in the tube bundle, and this rotates them because they are subjected to constant torque. This type of engine is called the "Curie wheel". Indeed, in the literature there are a lot of other examples of thermo magnetic motors.

The prototype developed by UNIFESP is a linear reciprocating thermo magnetic motor [16]. Essentially the motor is composed by: x a dozen permanent magnets in Neodymium Iron Boron (NdFeB;)

x two plates made of magnetic materials ($Gd_{4.7}Nd_{0.3}Si$) with internal channels for the flow of heat exchange fluid.

The proposed thermo magnetic motor works with hot source given by flat solar collectors and cold source at room temperature. Figure 3 shows a schematic representation of the motor.

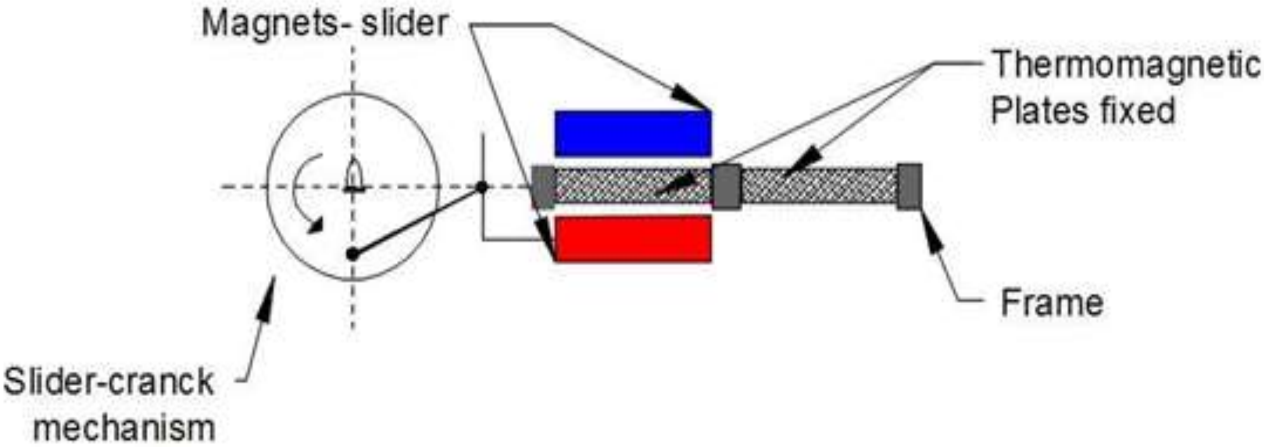

Fig. 3. Schematic draft of the linear reciprocating thermo magnetic motor

The temperature gradient adopted is between 70-80 °C (hot source) and room temperature 25 °C (cold source). The heat exchange fluid used is water. The device works using, initially, the hot water that crosses the left plate and which changes its magnetic state, becoming paramagnetic, so releasing the magnets toward the plate placed at the right side and which is cooled by cold water and magnetized. After the magnets movement, a sensor changes the flow of the hot water to the right plate and the cold water to the left plate, and a new movement of the magnets occurs.

The hydraulic valves and other sensors are used to regulate uniform and regular working operations. The permanent magnets an oscillatory movement is transformed into revolving movement through a slider-crank mechanism and the total power produced is around 5.53 mW. This value depends by a several number of variables like the operational period of the motor. All technical details have been clarified in Ref [16]. Figure 4 is a picture of the motor.
It's clear that the total power produced is very low but some improvements can be made. In fact, one possibility may be use the heat transfer system that not uses exchange fluid.

Fig. 4. Picture of the linear reciprocating thermo magnetic motor (global view.)

In order to obtain another draft design of a thermo magnetic motor, new researches and studies are being performed. The innovative idea is the development of a thermo magnetic motor without heat transfer fluids to exchange. The main advantage is a reduction of complicated mechanical subsystems and components as valves or hydraulic pumps.

We can consider some industrial applications and use in food factories (for example in the soluble coffee factory) or the organic waste thermal treatment.

Another possibility is the development of motors to work with high temperature hot sources, such as provided by cylindrical parabolic solar collectors, capable of delivering temperatures between 200°C and 600°C or spherical parabolic solar collectors capable of delivering temperatures between 300°C and 1000°C.

In these cases, E.golf et al. [17] have theoretically shown that energy and energetic efficiencies are considerable, and for magnetic fields above 1.5 T, achievable with permanent magnets up to 2 T. The study underlines that it may be greater than those associated with steam turbines.

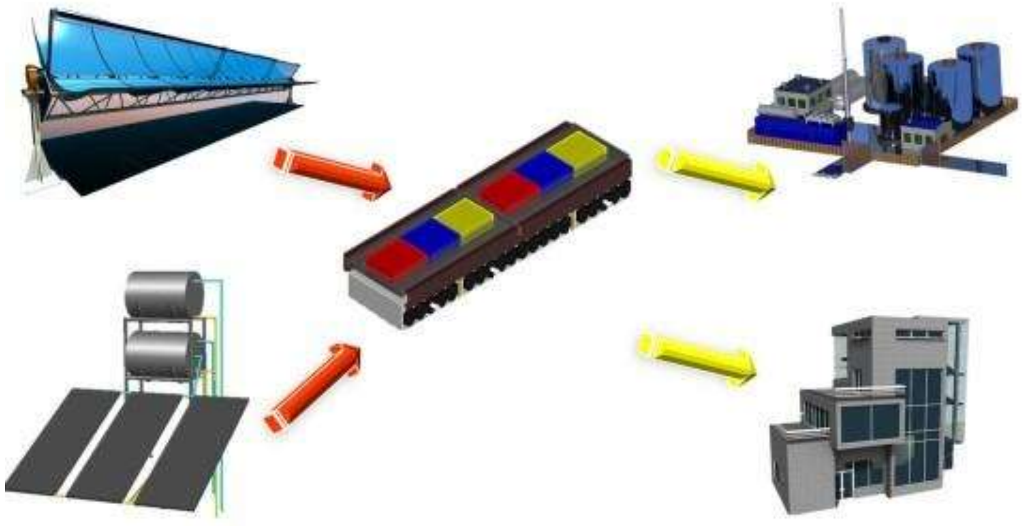

Fig.5. Renewable systems coupled with thermo magnetic conversion devices for residential or industrial sector.

IV. ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

Recently some studies put more attention about the green design of new technologies. The aim of this paragraph is environmental analysis of the prototype and economic feasibility study considering the motor above described and realized in UNIFESP.

A. Environmental analysis

The purpose of this section is to describe all technical information about potential environmental and health effects and impacts of the thermo magnetic motor proposed. In fact, the environmental impact of the rare- earth elements used is quite high.

The impact of emissions, other environmental pressures and resource competition on human health is an important area of concern for individuals in many countries [18].Generally, the parameters usually used to classify environmental impacts are:

- Human health that is s assessed using the Disability *Adjusted Life Year (DALY),* a time-based measure that combines years of life lost due to premature mortality and life quality lost due to time spent in states of less than full health;
- Ecosystem quality that analyzes the damage to ecosystem quality through the measure of *Potentially Disappeared Fraction of plant species (PDF).*
- Resources Depletion that reflects the many ways human activity uses up the Earth's natural resources. "Depletion" means that those resources are no longer available for further use in their highest-value forms;
- Global Warming: climate change impact is often referred to as its "carbon footprint" because global warming potential is usually measured in units of carbon dioxide equivalent

The materials used for the fulfillment of the described thermo magnetic motor are gadolinium, neodymium, silicon and aluminum. The study is been completed using specific data [19], [20] to evaluate their impacts. Thus, the model computes the above-mentioned environmental impacts. Figures 6 shows the results for the rare earth elements utilized.

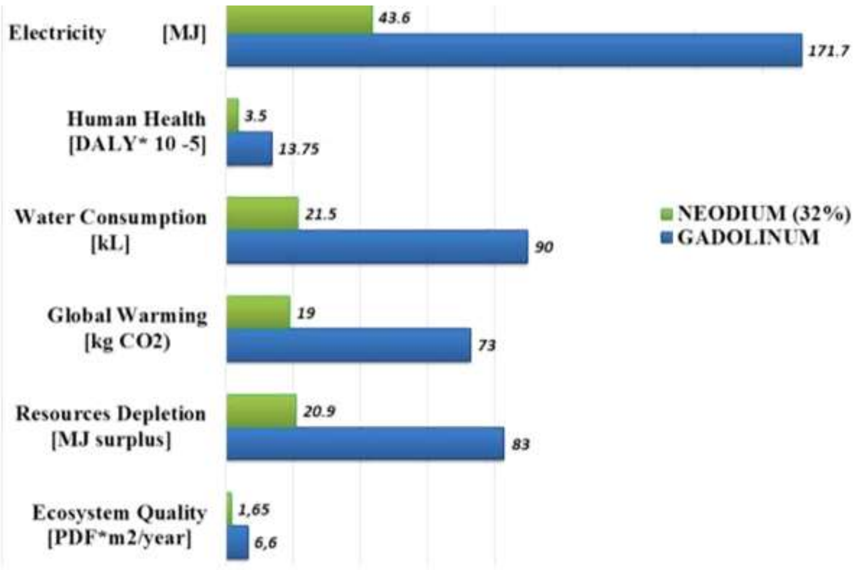

Fig. 6. Environmental impacts for the mass of the materials used (Gadolinium and Neodium)

Naturally, the mass of gadolinium used to make thermo magnetic plates has a high impact in all environmental categories researched. The unexpected outcomes are the elevated values for the aluminum because a big quantity is employed to assemble the structural base of the motor. The software used to assess impacts of the aluminum structure is SimaPro.

B. Economic evaluation

The goal of this final section is an evaluation of the economic potential and the cost of the thermo magnetic motor. The investigation includes estimations of the costs for a particular part of the magnetic prototype, as well as by taking into account the operating costs of a particular device. We underline that the study does not include:

- Pump and pipe work costs;
- Costs of valves, sensors, control and regulation system;

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After an accurate market analysis, we considered the costs presented in table 2.

TABLE. II. ECONOMIC STUDY OF EACH SINGLE COMPONENT

Sl. No	*Component*	Costs
		Average Unit Price [€/kg]
1	Gadolinium	1000
2	Permanent Magnets in Neodymium Iron Boron (Nd Fe B)	30
3	Aluminium	4
4	Silicon	16

In this case, the choice of gadolinium increases a lot of the manufacturing cost of the device; sure enough, the cost of the chosen thermo magnetic material represents 55% of the initial production budget.

V. CONCLUSIONS

In conclusion, the initial part of the work outlines that the thermo magnetic motors could represent a novel interesting example of energy harvesting. The linear reciprocating motor developed represents an example. Although the low total power produced, several improvements will be made in future prototypes to increase the motor's power. The final sections underline that gadolinium has a remarkable impact on the environment and the initial cost of the project.

A possible solution is the adoption of other thermo magnetic materials free of rare-earths components to build the core of the motor.

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