Life Cycle Assessment of Thermomagnetic Motors: A Review

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Abstract. In view of the increasing demand for energy and the search for sustainable alternatives to traditional sources such as fossil fuels, the waste of thermal energy in industries and the potential for converting it into other types of energy are highlighted. The importance of Life Cycle Assessment (LCA) as a tool for analyzing the sustainability of complex systems is presented, covering all stages from the extraction of raw materials to the final product. LCA case studies in thermal waste reuse systems are exemplified by research that evaluates the environmental impact of technologies such as the organic Rankine cycle and the Kalina cycle. The application of LCA to thermomagnetic motors is proposed as a gap in current research, since they also reuse low-quality thermal waste to convert thermal energy into mechanical energy, emphasizing the importance of understanding the life cycle of these devices and their environmental impact. Another important point is the relevance of LCA in analyzing innovative technologies for producing energy from waste. Finally, it is concluded that LCA is fundamental for evaluating systems that use thermal waste, such as thermomagnetic motors, and highlights its role in the search for more sustainable energy sources, helping to guide policies and practices in energy production.

Keywords. Life cycle assessment, thermomagnetic motor, industrial waste heat.

1. Introduction

In recent years, because of the growing demand for energy and the environmental impact of its production, a considerable amount of discussion has focused on the use of alternative technologies, many of which are considered sustainable and theoretically have a lower environmental impact than traditional sources, such as fossil fuels. Other than that, the waste of thermal energy due to burning fuels is an important fact: data from 2014 from the United States Department of Energy (DOE) indicates that the energy currently wasted by US industries could produce up to 20% of the total US electricity production and reduce emissions of greenhouse gases by 20% [1]. The usage and conversion of this unused energy into other forms (mechanical or electrical) has been the subject of research, resulting in the development of various systems. In recent decades, numerous technologies to reutilize this energy that would otherwise be lost have been examined and proposed. Examples include the Organic Rankine Cycle (ORC), the Kalina Cycle, the Seebeck effect (thermoelectric), and thermomagnetic systems [2].

Thermomagnetic systems convert thermal energy into another type of energy due to the process of magnetization and demagnetization at the Curie temperature, at which point magnetic properties are lost. Among these systems are thermomagnetic motors, which result in the conversion of thermal energy into mechanical energy, and became an object of interest in recent research due to the advances made in the design of high-performance magnetic materials and in the better understanding of thermal transport [3].

With the advance and interest in the development of this type of device, life cycle assessment (LCA) is necessary, since it is an analytical technique used to analyze the sustainability benefits and trade-offs resulting from complex systems. [4]. LCA refers to the study of all the stages of production and use of the product, from the extraction of primary materials, including production, and distribution to consumption and final use, including recycling and reuse when appropriate.

The knowledge search about the potential impacts of each energy source motivates the development of scientific research on the topic. Therefore, this article aims to present a literature review on the application of HVAC in some types of technologies that reuse industrial thermal waste and propose how it could be applied to thermomagnetic motors.

2. Life Cycle Assessment (LCA)

2.1 Principles of Life Cycle Assessment

According to ISO 14040:2006 [5], that regulates, describes the principles, and covers Life Cycle Assessment (LCA) studies, this technique was developed out of concern for environmental protection and the impact of products, whether manufactured or consumed. Thus, there are four phases in an LCA study (Fig. 1): a) the objective and scope definition, b) the inventory analysis, c) the impact assessment, and d) the interpretation. The first phase depends on the subject of investigation and the intended use of the results generated and is essential for interpreting the results of the study [6,7]. The second phase studies all the processes that were identified as part of the system in question, including a detailed list of all incoming and outgoing material and process data [7,8]. The third phase focuses on determining the environmental importance of the inventory results using models, which reflect the physical flows and interventions of the system, making the methodology dependent on the functioning of the system studied [5,8,9]. Finally, the last phase is about interpretation of the previous ones. Therefore, LCA can be applied to assess the environmental impact that low-quality thermal waste reuse devices can produce if implemented.

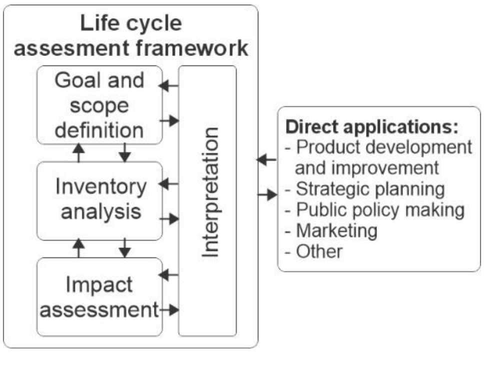

Fig. 1 - Stages of an LCA [5]

2.2 Case Study Analysis: Applying LCA to Low-Quality Heat Recovery Systems

Liu et al. [10] developed a study to assess the environmental impact of an organic Rankine cycle for waste heat recovery by applying LCA. According to the authors, even though the technology reduces CO_2 emissions compared to conventional power plants, there aren't studies reporting the environmental impact that the development of this system could aggregate. The LCA was divided into phases and investigated using different working fluids. As result of the study, the construction phase of the cycle is the most favorable for the global warming potential and eutrophication potential; the operation phase in two of the seven fluids contributes to the acidification and human toxicity potential, while the same aspects in the remaining working fluids contribute in the construction phase. The potential for global warming was considered the most serious environmental impact, followed by the human toxicity impact.

Another study conducted by Xie et al. [11] applies LCA to a multi-objective optimization model to evaluate the environmental performance of an integrated system combining $LiBr/H_2O$ absorption chiller and Kalina cycle. The Kalina cycle (KC) is a waste heat recovery technology for electricity production, in this case, it was integrated with the absorption refrigeration cycle to achieve full utilization of low-quality waste heat [12]. In the present study, this combination of multi-objective optimization and life cycle assessment aims to achieve the optimum energy, economic, and environmental performance of this integrated system. As a result, they concluded that the critical phases for environmental damage are construction, transportation, and demolition. However, the usage stage, especially in the production of electricity, influences the final results of the LCA the most.

Kallis et al. [8] also conducted a study using the Organic Rankine Cycle. This study, based in Athens, Greece, was detailed documentation of all the main components and processes of the system throughout the entire life cycle of the cycle system. Some of the results presented showed that the working fluid produces a major impact on ozone depletion and global warming categories.

3. Thermomagnetic motors

Thermomagnetic motors are devices that go through cycles of temperature and magnetic field to produce mechanical energy and are characterized by their ability to use a system for reusing low-quality thermal waste. Its advantages consist in transforming thermal energy that would be wasted into kinetic energy [13–15].

The study by Kaneko et al. [15,16] presents the design and construction of a Tesla-type motor, with a double-C magnetic circuit and heat exchangers containing thermomagnetic material, a component used to move the motor as a result of the thermal exchange that takes place between the material and the fluid, without the use of gravity or spring to operate. It had a maximum power of 0.41W.

Another work worth mentioning is that developed by Evaristo et al. [14] presented a thermomagnetic motor that uses the gravitational force to balance the magnetic force, employing a linear movement. The proposed motor design features a C-shaped magnetic circuit and employs Gadolinium as the material in the magnetic heat exchanger, very similar to the work in

[15]. The geometry of the heat exchanger is prismatic, with a rectangular cross-section and a circular channel in the center for the fluid flow. The studied motor showed a power output of around 0.4W.

3.1 Applying LCA to thermomagnetic motors

The majority of thermal energy not used when it is produced is classified as low-quality waste heat. Due to the low profitability provided by low efficiency in low-temperature gradients [17,18]. As a result, some studies have brought the use of thermomagnetic materials, which have a Curie temperature when the material loses its magnetism characteristic close to room temperature, to the development of thermal machines.[14,15,18].

Most of the work and studies about thermomagnetic motors are recent [3], the first motors were developed by Thomas Edison [19] and Nikolas Tesla [20] in the years 1888 and 1889. Both of them proposed the thermomagnetic effect as a means of converting mechanical energy, but due to the limited technology and materials at the time, little research was done on this type of technology until the last century.

Thus, the importance of LCA in understanding the environmental impact of any process makes it necessary to apply it to this type of motor that reuses thermal waste. In the scientific databases available, no mention is made of life cycle assessment applied to thermomagnetic motors. Therefore, integrating these two aspects, lead to some relevant questions such as: what is the life cycle of the motor; how long would it last; how does the acquisition of its main components take place: thermomagnetic materials; how does maintenance work; is the power generated by the motor economically viable; how the flows of matter and energy involved are measured and related to various categories of environmental impact; how to measure atmospheric emissions, as well as solid and aqueous waste from all process steps.

In view of these points, the following image (Fig. 2) exemplifies the criteria for measurement of the LCA applied to the development of this kind of devices. Furthermore, LCAs are being considered one of the most powerful tools for supporting decision-making processes used in sustainable production [21].

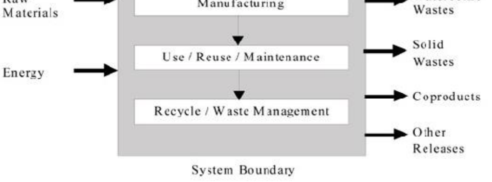

Fig. 2 - Life Cycle Stages [22]

Another study by Mayer, Bhandari and Gäth [23] aimed to analyze 315 peer-reviewed studies on the life cycle assessment of conventional and innovative waste-to-energy technologies. This presented as a decisive factor in the analysis that advanced treatment technologies can improve ecological performance compared to widely used conventional conversion technologies.

In this context, Ekvall et al. [24] studies has an important contribution to LCA concept to evaluating the environmental impacts of waste management. According to the authors, LCA broadens the perspective beyond the waste management system and it is relevant because indirect environmental impacts from adjacent systems, such as energy generation and material production, often outweigh the direct impacts of the system itself.

4. Conclusion and Final Considerations

The research presented emphasizes the importance of Life Cycle Assessment (LCA) in the analysis of systems that aim to make use of low-quality thermal waste, such as thermomagnetic motors. This technique is proving important for understanding the sustainability benefits and paybacks resulting from this type of technology, and it is also significant for supporting decisions on sustainable production. Integrating LCA into research on thermomagnetic motors offers new perspectives for more sustainable energy sources, and provides essential data to guide policies and practices towards energy production that uses industrial waste otherwise discarded.

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