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Environmental Impacts Analysis for Inkjet Printed Paper-Based Bio-Patch

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***Abstract*—This paper presents comparative environment impact evaluation and assessment between inkjet printing technology based Electrocardiography (ECG) Bio-patch and traditional Printed Circuit Board (PCB) based ECG Holters. Due to the complexity of electronic systems and the consistent lack of solid data about a product's life cycles, a limited comparison has been carried out to qualify the input and output of raw material resources, energy resources used in manufacturing phases and environmental emissions in end-of-life phases. Based on the GaBi's balance calculation methodology, a case study is described to illustrated the possibility of environmental potential benefits from above mentioned technologies.**

Keywords—Life Cycle Assessment, Printed and Flexible Electronics, Hazardous Emission, Bio-patch

I. Introduction

Nowadays the wearable medical or healthcare devices become more and more widely use in pervasive and personalized healthcare systems, especially in chronic diseases treatment area [1]. Continuous and non-invasive heart condition monitoring is one of the promising applications in telemedicine, where electrocardiography (ECG) signal is measured in a real time manner to facilitate the remote physicians or medical professionals to analyze and diagnose the heart condition of a specific user or patient [2]. A wearable Bio-patch [3-5] has been developed which can be easily attached on user's chest for continuous measurement of a user's cardiac signal. In order to make the developed patch unobtrusive, flexible, easy to use, and comfortable to patients, advanced printing technology has been used for the manufacture the patch where the conductive metal particles contained inks are directly printed on soft substrate to form the circuits' pattern [6]. The concept of the printed Bio-patch is illustrated in Fig.1. It is fabricated using nano-metal particle contained inks, with the aim of low-cost and disposable after use, which solves problems such as cable tangling, structure failure, as well as hygienic and environmental issues [7-9]. It should be noticed that the related environmental impacts of the emerging printed or flexible electronics are drawing considerable attentions due to its favorable features and huge potential to be applied in numerous applications. As over 80% of a product's environmental load is determined by the choices made in the early design phase, significant emphasis of this work has been put on environmental load analysis of the proposed ink-jet printing manufacture approach.

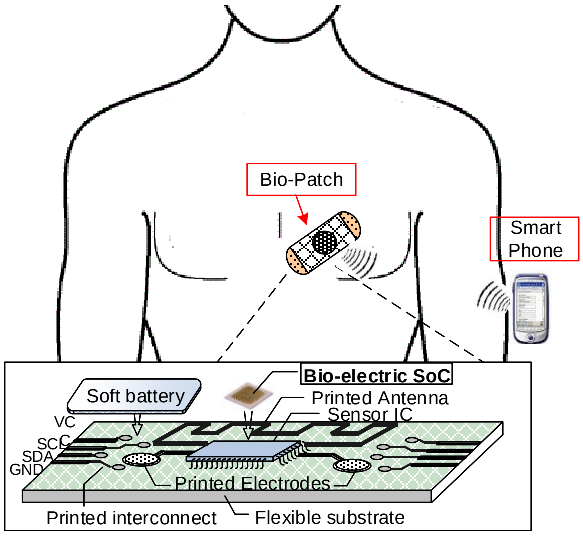

Fig.1. *Concept of Bio-Patch based ECG system [5]*

In this paper, we focus on assessment and analysis of the environment impacts of printed electronics by leveraging life cycle assessment tool. Substantial research has been conducted on several key areas which are related to the Life Cycle Assessment (LCA) and environmental impact analysis of printed electronics materials. In previous works, sustainability evaluation, environment assessment and toxic emissions of printed antenna, sensors, as well as flat active ECG cables have been investigated [10-15]. The focus of this work is to investigate the environmental impact of printed Bio-patch by quantifying its total environmental emissions and make a comparison with traditional printed circuits board (PCB) based ECG recording devices in the life cycle stages of raw materials preparation and production processing.

II. Life Cycle Assessment

LCA has been recognized as a user-friendly and efficient tool for assessing the overall environmental impacts of a variety of products, processes or services [16]. LCA is a tool which is capable of collecting and evaluating quantitative data on the inputs and outputs of material, energy and waste flows associated with a product throughout its entire life cycle, so that the environmental impacts can be determined [17].

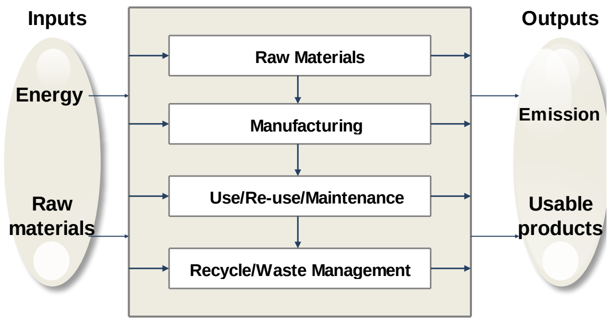

Fig.2. *Product life-cycle stages*

The major stages in an LCA mainly include raw material acquisition, materials manufacture, production, use/reuse/maintenance, and the latter stage of waste management. The defined boundaries, assumptions, and conventions to be addressed in each stage are presented. Figure 2 shows the life cycle assessment stages and boundaries of a product: the resource flows (e.g., material and energy inputs) and the emissions, waste, and product flows (e.g., outputs) within each life-cycle stage, as well as the interaction between each stage are evaluated to determine the environmental impacts [18].

By leveraging LCA we can compare the full range of environmental effects assignable to specific products and services by quantifying all inputs and outputs of material flows and assessing how these material flows impact our environment [19]. The obtained information can be used to guide or improve processes, support policy and provide a sound basis for viable solutions [20].

Life cycle assessment is defined as comprising four interrelated components as a phased approach briefly discussed as below.

A. Goal and scope definition

As the first step lays out the rationalization for conducting the LCA and its general intent [21], as well as specifying the product systems and data categories to be studied, this paper presents LCA for both inkjet printed ECG Bio-patch and conventional PCB based ECG holters. The aim is to establish environmental evaluation of the new technology inkjet printing products by comparing it with a conventional technology.

B. Inventory analysis

For quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste, and other environmental releases of both Bio-patch and traditional holters, due to the lack of reliable life cycle inventory input and output data with newly invented technology[22], the GaBi software and database is chosen here as a life cycle engineering tool in this case for inventory analysis.

C. Impact assessment

To characterize and assess the effects of the environmental loadings identified in the inventory component, comparisons between Bio-patch and PCB based holters have been conducted in this work.

D. Improvement assessment

As a systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw materials use and environmental releases through-out the whole life cycle of the product, process or activity. This assessment should include both quantitative and qualitative measures of improvements [23].

III. Procedural Flow Diagram

In order to make a thorough comparison, life cycle assessment has been made for the inkjet printed Bio-patch as well as rigid PCB based ECG Holters. The procedural flow diagram is based on Gabi's balance calculation as shown in Fig.3. Each step of the LCA methodology is briefly discussed in the succeeding sections.

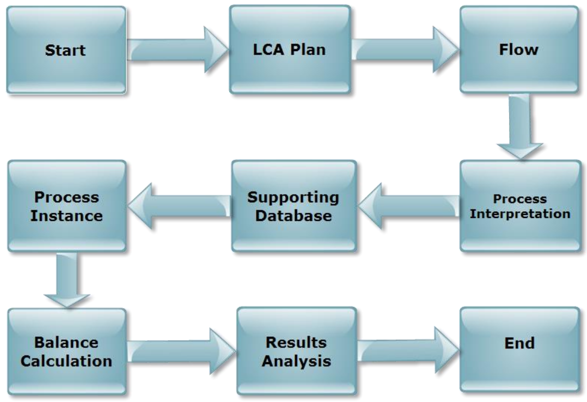

Fig.3. *Procedural Flow Diagram for Life Cycle Analyzing of the Developed Bio-Patch*

A plan in the inventory analysis tool is the basis for connecting different processes and thereby, modeling the steps of printed electronics life cycle, which is a representation of the system boundaries [10]. Fig. 4 and Fig. 5 show the plan for LCA structure of Printed Bio-Patch and PCB technology respectively. Each flow is the fundamental unit in life cycle assessment software which shows the material or energy flow between every two processes. The specified database is allowed to support the existing process during the process interpretation. All the processes represent the inventory for producing valuable substance such as polyamides substrate, conductive ink and electrical components in this case. The supporting database comprises of inputs and outputs for the specified process. The inputs are in the category of renewable resources, non-renewable resources, minerals, waste for recovery, thermal energy and so on. Similarly the output represents environmental impact such as inorganic/organic emissions to fresh water/air/sea water, heavy metals to air, hydrocarbons to fresh water and so on. The process instance is the local process settings after the plan is completed with the set of processes and corresponding flows [11] [12].

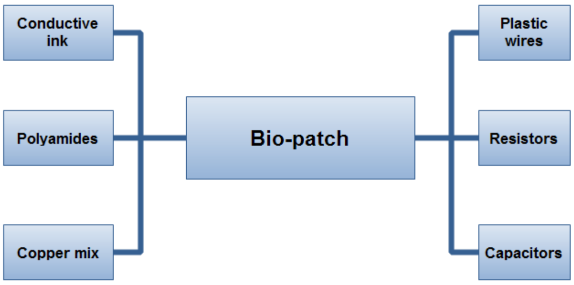

Fig.4. *Plan for LCA structure of Bio-Patch*

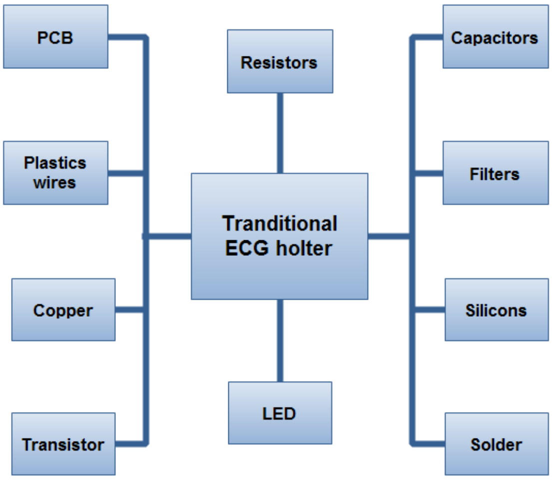

Fig.5. *Plan for LCA structure of ECG Holters*

IV. Results Analysis

This section of work thoroughly deals with the results obtained in both technologies i.e. Printed Bio-Patch and traditional PCB technology.

A. Results from Printed Bio-Patch Technology

For the production of 10,000 printed Bio-Patch, Fig. 6 visibly shows the total environmental emissions. The dominating emission to the environment is to fresh water. The data shows that 98% of emissions are into fresh water and remaining 2% for emissions to the air, and sea water. Our design of printed Bio-Patch consumes most significant materials as polyamides substrate and conductive ink. Fig. 6 explicitly shows the total environmental emissions caused by these two materials. From input balance resources, it is noticed that conductive ink utilizes 1927.6 Kg of non-renewable energy resources whereas polyamides sheet uses mostly renewable material resources. Nonrenewable resources normally contain cop-per-gold-silver ore as a majority composition whereas quartz sand, rock salt, limestone, zinc-copper ore and zinc-lead copper ore are the minority components. Similarly the majority components of renewable resources are water and air. There are different categories of water resources such as feed water, ground water, river water, sea water, surface water and well water. Among these categories polyamides mostly consumes river water and its quantity is 1918.3 Kg.

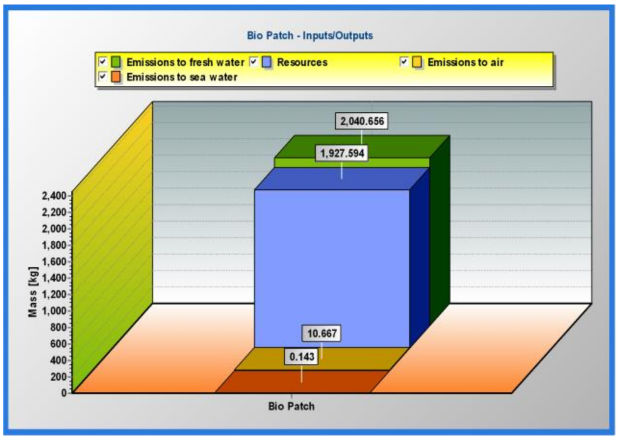

Fig.6. *Total Environmental Emissions of Bio-patch*

B. Environmental Emissions due to Printed Bio-Patch

The following sections illustrate the environmental emissions to air, fresh water, sea water and industrial soil.

- Emissions to Air

Printed Bio-Patch produces harmful emissions to air mainly due to inorganic emissions, organic emissions, heavy metals to air, particles to air and radioactive emissions to air. An inorganic emission contains components like ammonia, carbon dioxide, carbon monoxide, steam and so on. Among total environmental emissions to air, the percentage of inorganic emissions and other emissions are respectively 51% and 48%. Remaining 1% is for rest of the emissions. The other emissions to air consists of the materials such as heavy metals to air, group PAH to air and halogenated organic emissions to air. The mass of total emissions to air is negligible compared to other emissions.

- Emissions to Water

An emission to water includes the following components. They are analytical measures to fresh water, radioactive emissions to fresh water and particles to fresh water shown in Fig. 7.

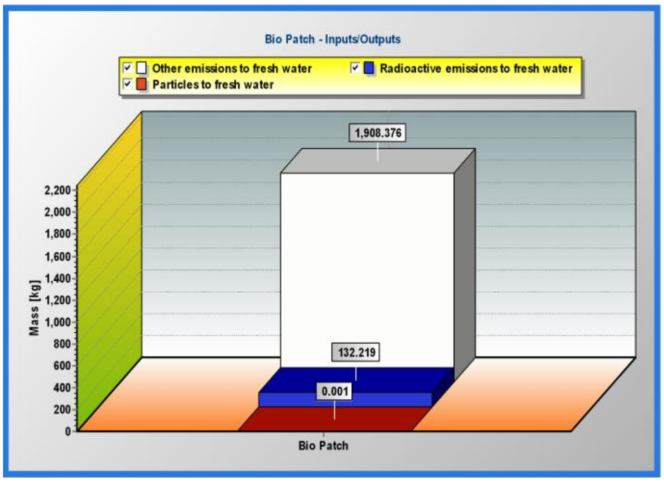

Fig.7. *Emissions to Fresh Water*

It has been clearly mentioned that total emission in use phase of Bio-Patch produces 1908.4 kg emission to the fresh water out of which 65% produced by Polyamides substrate and 17% by conductive ink. The total amount of emission due to Bio-patch is shown in Fig. 7. There are different categories of emissions to the fresh water. The dominating emission to fresh water is due to inorganic components. The inorganic components in general include chloride, carbonate, fluoride, sulphate and sodium as the major constituents. The other emissions to fresh water are due to heavy metals, halogenated organic emissions and hydrocarbons. The quantities of these emissions are very low compared to inorganic emissions and analytic measures to fresh water. The metals antimony, arsenic, cadmium, chromium, cobalt, iron, lead and mercury are the major constituents in the category of heavy metals to fresh water. [23] Similarly there are emissions of particles to fresh water.

An emission to sea water is mainly due to copper component of Bio-Patch. There is no emission due to polyamides sheet to the sea water. The total quantity of emission to the sea water is around 0.2 kg for specified Bio-Patch mass in its use phase period. The analytic measures to the sea water contains absorbable organic halogen compound , biological oxygen demand, and chemical oxygen demand. Beside these components heavy metals to sea water is also contaminated. inorganic emissions to sea water, hydrocarbons to sea water, Naphthalene and suspended solids are shown as the major composition of the emission. The inorganic emissions to sea water dominate among others.

- Toxic Gas Emissions

With production of 10,000 printed Bio-Patch, it is evident that the toxic gas such as carbon dioxide, carbon monoxide, hydrogen, nitrogen dioxide, nitrogen oxides and sulpher dioxide are evolved during the raw material preparation stage. The emission of carbon dioxide is higher among all toxic emissions. With the emissions of 10.1 kg of carbon dioxide, 67% of emission is due to polyamides while 22% by conductive ink. Another dominating toxic emission is sulpher dioxide and it is 0.6 kg by mass. Out of this 0.6 kg emission, 66% occurred by polyamides where as 24% by conductive ink. The remaining toxic emissions are significantly lesser than carbon dioxide and sulpher dioxide.

C. Results from PCB Technology

This section of work deals with analysis of environmental emissions for the production of 10,000 PCB based ECG Holters. For the production of 10,000 PCB Holters, Fig.8 clearly shows the total environmental emissions. The dominating emission to the environment is to fresh water. The data shows that 99% of emissions are into fresh water, 1% to the air ,sea water and industrial soil.

The following sections illustrate the environmental emissions to air, fresh water, sea water and industrial soil from PCB based Holter.

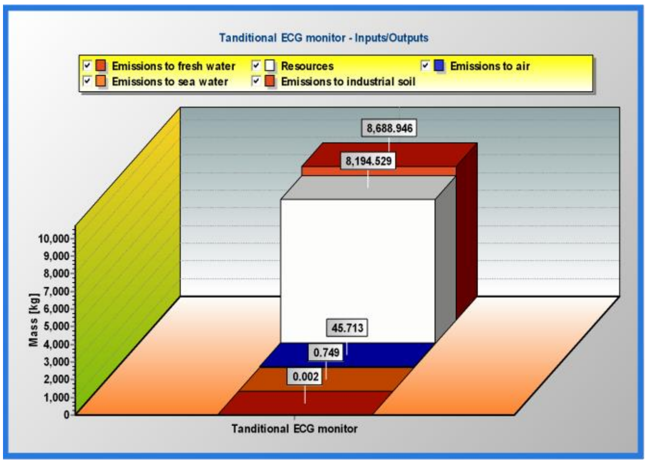

Fig.8. *Total Environmental Emissions of PCB Holter*

- Emissions to Air

PCB Holter produces harmful emissions to air mainly due to inorganic emissions, organic emissions, heavy metals to air, particles to air and radioactive emissions to air. An inorganic emission contains components like ammonia, carbon dioxide, carbon monoxide, steam and so on. Among total environmental emissions to air, the percentage of other emissions and inorganic emissions are respectively 23% and 68% respectively. Remaining 9% is for rest of the emissions. The other emissions to air consists of the materials such as heavy metals to air, group PAH to air and halogenated organic emissions to air. There are other emissions to air such as organic emission, radioactive emission to air and particles to air. The amount of these emissions is negligible compared to inorganic emission.

- Emissions to Fresh Water

An emission to fresh water includes the following components. They are analytical measures to fresh water, heavy metals to fresh water, inorganic and organic emission to fresh water and some other emissions. It has been clearly mentioned that total emission in use phase of PCB Holter produces 8688.9 kg emission to the fresh water out of which 89% is generated by other emissions, 10% by radioactive emissions and 1% by heavy metals, organic emissions and particles respectively. The dominating emission to fresh water is due to inorganic components. The inorganic components in general include chloride, calcium, fluoride, carbonate, fluoride, sulphate, hydroxide and sodium as the major constituents.

- Emissions to Sea Water

An emission to sea water is mainly due to active and passive component of PCB Holter. There is no emission due to plastics part and copper wire to the sea water. The total quantity of emission to the sea water is around 0.8 kg for specified PCB Holter mass in its use phase period. The analytic measures to the sea water contain absorbable organic halogen compound biological oxygen demand and chemical oxygen demand. Beside these components heavy metals to sea water is also contaminated. The inorganic emissions to sea water dominate among others. 93% of emission to sea water is due to inorganic emissions.

- Emissions to Industrial soil

Total emissions with a production of 10,000 PCB Holter causes very little emission to industrial soil. These emissions involve inorganic emissions, heavy metals and organic emissions. The percentage of these emissions are 65%, 26%, and 9% respectively.

- Toxic Gas Emissions

With production of PCB Holters, it is evident that the toxic gas such as carbon dioxide, carbon monoxide, hydrogen, nitrogen dioxide, nitrogen oxides and sulpher dioxide are evolved during the raw material preparation stage. The emission of carbon dioxide is higher among all toxic emissions. The mass of different emissions are as follows. Carbon dioxide – 3.9 kg, carbon monoxide – 800 gram, Hydrogen – 87 gram, nitrogen dioxide – 15 gram, Nitrogen oxides – 21 gram and exhaust - 11 kg. The remaining toxic emissions are significantly lesser than carbon dioxide and sulpher dioxide.

- Comparison and assessment for Printed Bio-patch and Traditional PCB

In comparison with traditional circuit manufacturing by the mentioned quantitative data for the total emissions, emissions to air, emissions to fresh water and toxic emissions, a total mass of emission in production of traditional PCB Holters is 8688.9 KG, which is 4 times more than the printed Bio-patch with the total emissions of 2040.7 KG, the foreground of inkjet printing is strong as it required and coursed much less resources and pollutions. Because Inkjet printing is an additive process to deposit the functional electronic materials only where needed allows the use of low-cost flexible substrate materials such as polyamides and even paper, whereas traditional PCBs manufacturing is a subtractive process which contains wet chemical etching progress. [24]- [26]

V. Conclusion

In this paper we have investigated the life cycle assessment and environmental impacts of printed Bio-patch by comparing with traditional PCB based ECG Holters. Our objective was to conceive life cycle assessment of printed Bio-patch in raw materials and manufacturing phase. The results shows printed Bio-patch is capable of being more environmental friendly than the convention PCB technology, and in production process, and the emissions from printed Bio-path to fresh water is significantly larger than emissions to air, sea and soils.

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