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.

II. LIFE CYCLE ASSESSMENT

LCA has been recognized as a user-friendly and efficient tool for assessing the overall environmental

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

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.

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.
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 sulphur 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 sulphur 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 sulphur 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.

- 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 sulphur 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 sulphur 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 process. [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.

ACKNOWLEDGMENT

This work was financially supported by Vinnova (The Swedish Governmental Agency for Innovation Systems) through iPack Vinn Excellence centers program at the Royal Institute of Technology (KTH), Stockholm, Sweden.

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