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Life Cycle Assessment of Monocrystalline Versus Polycrystalline Imported Photovoltaic Panels in Context of Energy

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***Abstract*—** Solar energy is one of the most promising and sustainable energy suppliers among other energies. Geologically Pakistan is residing in the territory of highest solar radiation fall in the world. The average radiation falls is range from 4.656 - 4.864 kWh/m^2/day daily on Pakistan. It shows the high potential solar energy exists in Pakistan, but still Pakistan is unsuccessful to trap solar energy in abundant manner due to many reason. Pakistan is facing energy crisis for many years and still many of the regions are not electrified due to accessibility and other issues. So the local people are using the standalone solar system for fulfilling the basic need but the survey found very bad quality solar panels selling in the market which are imported from china and other countries. However, it discourages indirectly the local people by using such panels by getting the low output. So this research is carried to conduct the life cycle assessment (LCA) of solar module. It is a technique that quantifies the product impact on the environment and identifies other important factors which ensure the quality and market development. In this research the LCA found the processes and operation used in manufacturing the solar module, which contribute larger part in the emission and energy consumption. The transformation of metallurgical grade silicon to solar grade silicon and panels assembly is the two main processes which consumed more than 70% of energy and take part in higher emission. The results showed 1416 MJ/panel and about 79 kg of equivalent CO2/panel generated. So it is proposed that Pakistan should start their manufacturing.

***Keywords*—** Energy Payback period (EPBT), Global warming potential (GWP).

I. INTRODUCTION

In last decade the energy demand in Pakistan is significantly increases. Pakistan has energy crisis and most of the rural areas are still not electrified. The Demand and supply gap is increasing every year. Due to such energy crisis the rural area has load shedding of about 16-18 hours and urban area faces 10-12 hours of shortfall during hot summer [1]. Geologically Pakistan territory reside in very high solar radiation [2]. On domestic level, people use solar panels to fulfil their basic need of energy; they used the imported solar panels of different companies.

Life cycle assessment (LCA) is a tool and technique used for the assessment of the product related with improvement and finding its impact and their potential throughout a product life [3]. Globally the non-renewable resources contribute the larger part in polluting the environment and create abundantly energy crisis [4]. Due to such worst resultant of non-renewable resources, the world start shifting toward the renewable energies, which pollute environment less than non-renewable resources or have high potential to save carbon emission in abundant manner [3,4]. Solar power is well known for having the high potential in free energy and capacity to decrease pollution, energy consuming reduction and end production of energy [3].

Since commencement of new century, the remarkable growth has been recorded in the solar PV manufacturing and market application [2,3]. The Chinese market in PV manufacturing results a rapid growth, advancement and act like the leader in the globe [4]. In current situation, the shipment of PV module reached to 27.4 GWp in 2013, which is about 50% of the whole shipment in the world. Moreover, the efficiency of the solar cell increase annually, it got increase from 12% to 18%, the mitigation in consumption of energy on production of solar grade silicon has also been experienced [6]. Additionally, the system cost and module cost are decreased as well [7]. Some of the researcher raised point against the energy yield of solar energy that it could not fulfil the atonement of consumed energy in manufacturing. Some other points also rose that it is not a clean energy because of hazard materials emitted during manufacturing of solar module especially when the molten grade silicon is converted into solar grade silicon [8]. It is difficult task to show the solid results or proof by considering only energy and material flows. There are different materials emission and energy consumed on different stages which have their own impacts on environment. Overall the Solar system is considered the clean system for energy production and also maintenance free. However, the pollution and the consumption of energy should account when considering the whole life cycle

of solar system [8]. The solar system produced certain amount of energy which provides the exceeded atonement of consumed energy during manufacturing [9]. Therefore, it is need to assess the life cycle of solar system to identify whether it is environmental friendly or not.The recent research has been done by California University and MIT, Stanford University on the energy and atmosphere program. Their studies found the atmospheric result of 139 countries which shows the solar radiation falls and potential of hydropower. The report reveals that Pakistan is one of the blessed countries in the world which has highest potential in solar energy, which can fulfil about 92% of energy requirement [4]. Figure-I-1 shows the map of solar radiation that falls daily on Pakistan territory which unveils the solar energy potential in Pakistan.

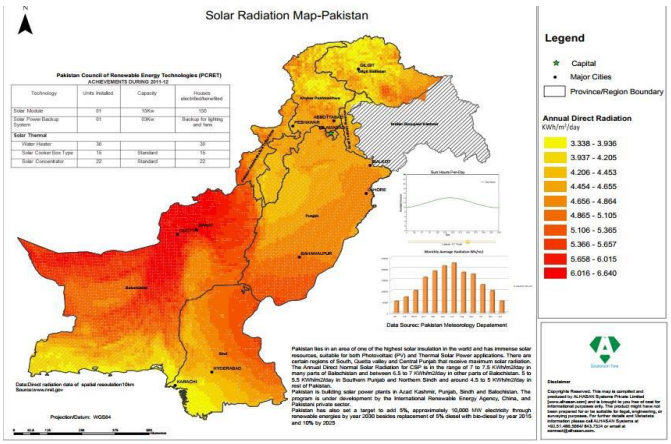

Figure –I-1 Solar Radiation Map of Pakistan [4]

Pakistan has currently few of their solar projects that are operational since last few years. The country need to be more relying on solar energy. To avail such potential of solar, Pakistan has to boost solar installation. Pakistan has only one solar grid in Bahawalpur Punjab that produces 100 MW of electricity [2]. In KPK the different companies of solar panels are available that have numbers of varieties and output. However, no standard company's panels found yet. There are three type of panels found, monocrystalline, polycrystalline and thin film, having different watts' output and Cost. But the survey found polycrystalline is the most selling panels. To find the more efficient and quality PV panels, it need to conduct the life cycle assessment (LCA) of solar Panels that are imported from china. LCA include the very first stage goal and product scope, the take analysis of inventories, after that assessment conduct of impacts and then finally interpretation [5]. The goal and scope of the LCA identify the objectives of the study, the functional unit and boundaries. The inventory analysis describes the different flows, resources and materials. These flows and hazards material which create the different environmental problems are aggregated and then assessments are taken for final conclusion in the interpretation stage [5]. It is the method for comparing the different products or products with different level for further improvement and environmental protection. After many decades' researcher realized that the human life and environmental protection is more important than technology development, so LCA is used as tool to find the potential for improvement in product. The LCA mainly used to account the sustainability of the product, greenhouse gas emission (GHGs) and energy payback time (EPBT) [10].

II. METHODOLOGY

LCA is one of the hard projects to undertake, I have used GaBi software for LCA. All the materials that are used for inflow and outflow like energies, emissions and recourses taking from very first like cradle to grave, are accounted for environmental impact assessment. The LCA methodology includes the goal and scope. The goal and scope define the boundaries of the systems or product, quality of data and many numerous materials. The LCA processes have different results for every process. According to ISO-14014 the standardized LCA can be perform by specified principles and frameworks, which leads to the correct LCA performing. There are four main phases in LCA, which are Goal and Scope, inventory Analysis, impact assessment and interpretation, which are shown in the below figure II-1 [5]. All other methods and process have taking under these phases and methods.

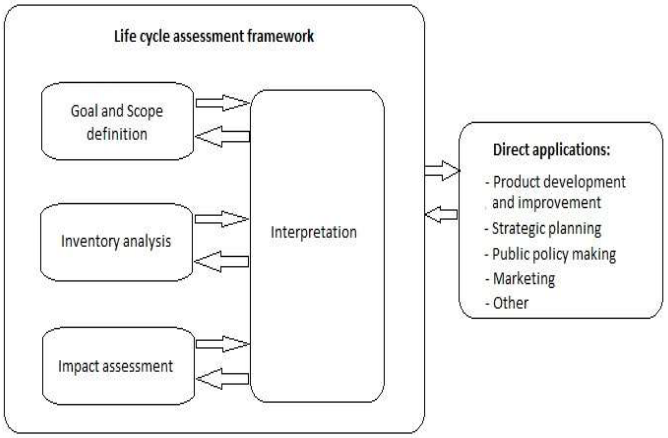

Figure II-1: charts shows LCA different stages

A. *Goal and Scope*

The Goal and Scope define the typical aspects that are commonly found in LCA. Some of the question that should be consider in goal and scope of LCA. The goal should define:

- Reason of this study carrying out
- The result will be used for
- Which product is using

There are many reasons for conducting LCA of Solar panels but researcher main focus will be the identification of sustainability domain of the monocrystalline versus polycrystalline imported solar panels for Pakistan territory, which are used locally in abundant manner[2]. Other reasons include the development of the product, providing best product to the customers and products comparison. The importance of goal also affects the scope side of LCA because of having interrelation with each other; the goal of your study may define the scope of your product study. It will settle the boundaries and circle of study [11]. Scope defines the boundaries of the product and it will fulfill goals. The scope includes the following steps and method. Selection of different function enables comparison between two products. It gives the quantified measurement of the services and performance. To quantify and measure the product, both FU should include all the inflow process and methods. In LCA the FU has very important role because of the comparison of the two products [12]. For example, if we take the solar panels of two different models of different companies, both have function to give the solar energy; it will give the comparison opportunity according to the territory suitability. The system will include those processes that are important for the LCA [13]. It is impossible to carry out all the process because sometime it includes most of the irrelevant process which later lead to the time consumption in LCA. So that is why the boundaries are described to conduct the relevant data [13].

- Natural systems defined boundaries
- Geographical systems defined boundaries
- Boundaries of time
- Other product Boundaries

A. Life cycle inventory (LCI)

The input or inflow resources and materials like water, energy, fuels and many other materials should be consider for the system studies during life cycle [14]. The materials that are emitted from the system like acidified liquid to the ground, hazardous gases to the air, other by-products and products should be identified. These in and out flow of the system at every stage and process should be quantified. The collected data should then present for assessment stage. To conduct the data, every input and output of the system should be monitored or measured [15]. There are some databases also available through which online data can be extracted. After collection of the specified data, it should be then categorizing, which would be arranged in categories as per impact on environment. The collected data is then calculated per function unit.

B. Impact Assessment

The impact assessment for pulling out the result in easy way [16]. The classification of the raw data limited the inventory analysis up to 15 categories for clear and easy consequences of the results. There is no specified categories for impact assessment because of absence of harmony on categories, that which categories should avoided and which should take, to solve such uncertainties general categories should be taking like effect on human health, recourses consumption and effects on ecology [17]. These main categories include the further sub categories which will identify data more effectively. The subcategories are shown in figure II-2. There are some of the compounds which are included in more than in one category; it should be mentioned. For example, the output of NO (nitrogen oxide) would be included in category of ozone depletion, GWP and acidification [18]. After collecting the data of elementary flow, the data should be categories in different category. It would be then translated into one single element that will represent the rest of compound potential called characterization [19]

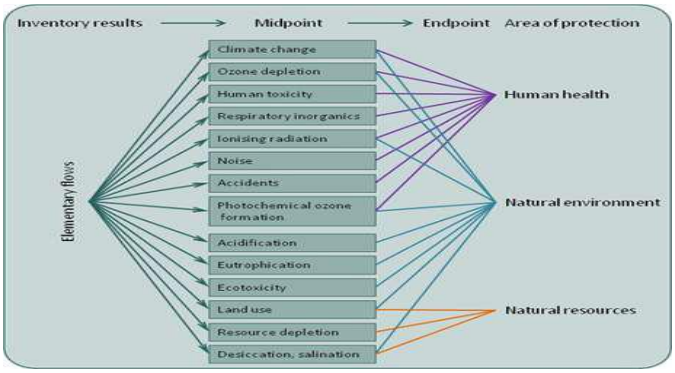

Figure II-2: charts shows LCA different stages

III. PROCESSES AND YIELDS

The results from this research include the three different phases of LCA for solar panels. These phases define the whole life cycle of this product and concluded the impacts on the Pakistan territory. These phases include the upstream, midstream and then the downstream. Upstream processes include quartz mining, solid grade silicon (sog-Si) purification, silicon ingot growth and wafer slicing and finally the production of modules. Midstream processes involve the installation, operation and then the outputs from their energy and CO2 emission. Lastly, downstream processes include PV system operation and retirement of PV stations, the decomposition of the solar panels and the reuse of the secondary input as primary input. Figure III-1 shows model of LCA.

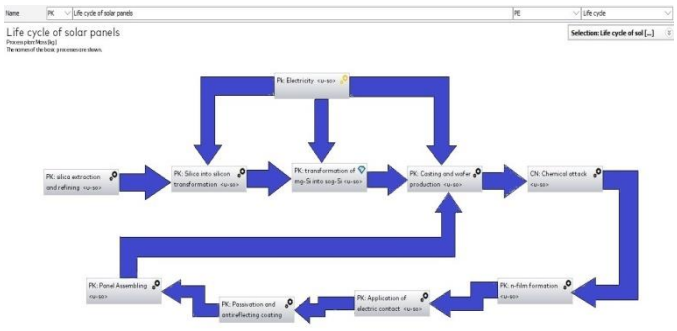

Figure III-1: Modeling LCA of solar panel

A. Upstream process

The simulation result shows the different process contribution in the output of the different materials and their percentage in Global Warming Potential (GWP). There are three processes which show the larger contribution in the GWP and energy consumption. One is the transformation of metallurgic

grade silicon to solar grade silicon, the second one is panel assembling and the other one is casting and wafers production. The first one contributes about 48% in the emission and consumes about 1180 MJ/panels. The casting and wafer production contribute 15% while the panels assembling create about 18% of material and consume 12 MJ/panel and 224.14 MJ/panels of energy. The rest processes have very less outflow. Some of them are very negligible output and energy consumption. Here is the proportionality method is suited in better manners. The processes which consume more energy are the main emitter of materials and have larger impact on environment. Some of the statistics are shown in the figure III-2.

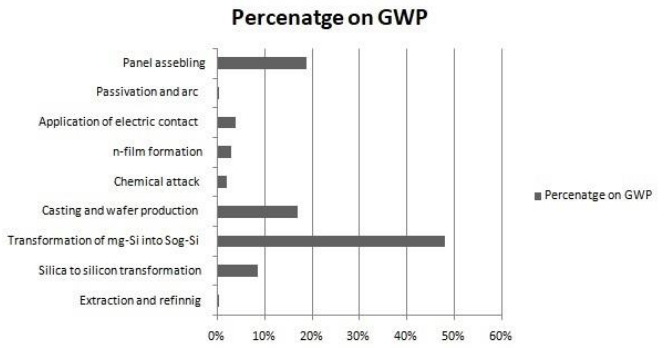

Figure III-2: Percentage on Global warming potential

Here are some other aspects that are account for the greater emissions and energy consumption. That is the use of methods, techniques and technology for the manufacturing of photovoltaic panels. The most advanced technology is nowadays used for the production of very efficient panels which have greater efficiency and have very low consumption and output, but they are not commercialize yet. Here is some of the research shows the contribution of each process in GWP, the emission of 314 kg-CO2 eq/m2. This emission is occurring for the production of multicrystalline panels of efficiency 16%.

i. Emission by solar wafer manufacturing

The emission due to solar wafer manufacturing includes the emission carbon dioxide, solvent, hazardous water, silicon dioxide, silicon dust, argon gas and many other materials as shown in the figure 4.3. A 6 % deficiency in silver paste usage can result the reduction in Impact on human life, marine ecosystems, and metal resources respectively which would be 4.43%, 5.13%, and 2.47%. All of these materials are taken according to the carbon dioxide equivalent. The impact potentials are comparing with carbon dioxide and simply multiply when it found more or less than carbon dioxide potential. The mineral oil is emitted in larger magnitude from the wafer manufacturing which is about the 15 g per wafer shown in the figure III-3. The second number is silicon carbide which is about 14 g per wafer. It can cause the lung cancer in animal, cause the eye irritation in human and resultant the respiratory difficulties in human and animals. The other high emission includes the KOH and argon gas. The KOH causes the damage of respiratory track, lung damages and other skin problems. It is very destructive to all body tissue and causes serious problem to human body. The argon gas causes Inhalation problem, the excessive inhalation causes the dizziness, vomiting, nausea, consciousness losing and finally death. So to avoid such serious impacts the manufacturing should be far from urban areas

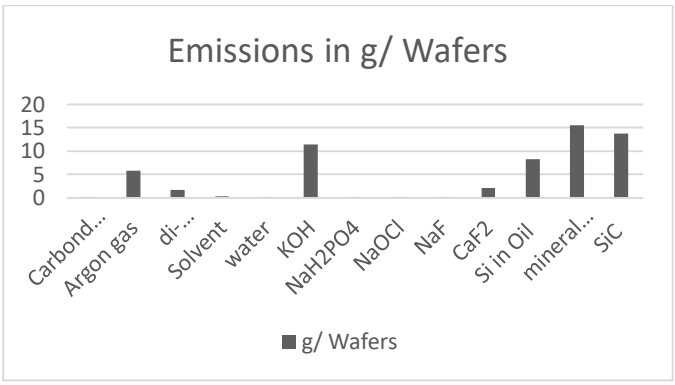

Figure III-3: Emission from wafer production

ii. Emission Due to molten grade silicon

Figure III-4 shows the emission of different material which are emitted due to the conversion of molten grade silicon (mg-Si) to solar grade silicon (Sog-Si). The high magnitude of emission includes the 4.7 kg of carbon dioxide (CO2) shown in figure 4.4, this emission is taken as equivalent of other chemical substances. The carbon dioxide is the hazardous substance for the environment. The main problem it causes is the respiratory system damages. Along with carbon dioxide and other outputs are accounted toxic for the marine life and human life. These emissions are related to the energy consumption. If the consumption of electricity reduced to 98 kWh/kWp, nearly 23.09%, 2.15%, 0.60%, and 25.80% of the total impact on environment in the specified matter production, toxicity of marine ecosystem, metal resources depletion, and fossil energy depletion will be curtailing respectively. The interpretation of these results describes the emission of certain materials are negligible. It cannot cause the serious impacts on the environment if some protective acts would apply.

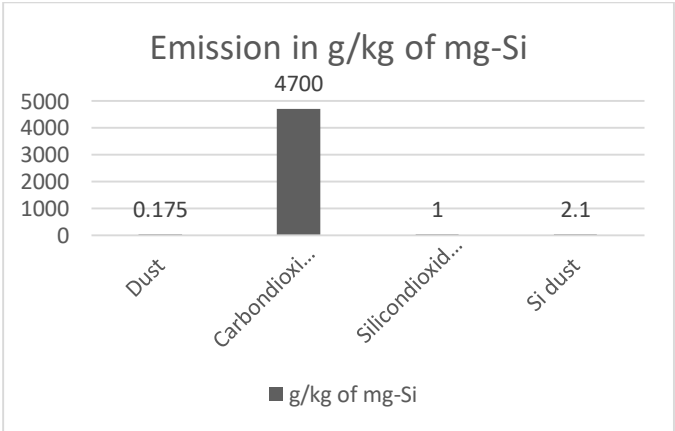

Figure III-4: Emission from molten grade silicon

iii. Emission due to solar grade silicon

The different materials are emitted from the production of solar grade silicon. These emissions include silicon dioxide, calcium fluoride and silicon dust shown in figure III-5. The high magnitudes of emission possess the calcium fluoride, which has greater contribution in climate change, marine toxicity and resources depletion. The critical impacts which contribute the dominant role in environmental burdens are human toxicity, threat to marine life and resources depletion. The other impacts which are resulted from non-renewable resources depletion, formation of matters and acidification of land have insignificant impact. Some other emissions are recorded from this operation but they are negligible

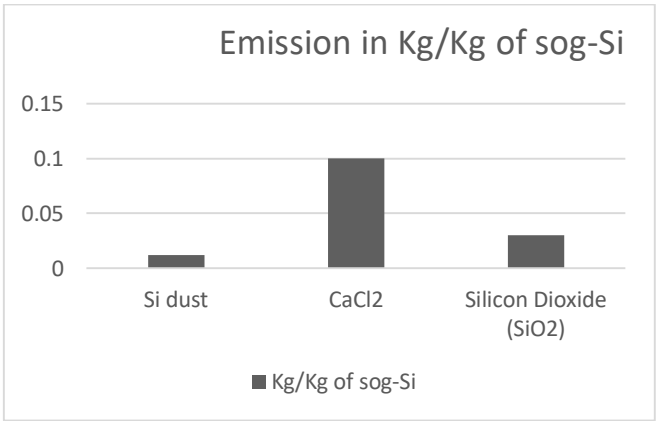

Figure III-5: Emission due to solar grade silicon

iv. Emissions Due to panel assembly

The panel assembly wastes include the EVA output, silicon adhesive and aluminium in abundant manner shown in figure 4.6. These materials contribute in soil contaminations, water, biotic and Abiotic impacts occur due to these wastes. The results show that the usage of wasted aluminium as primary aluminium, it can give the greater benefits to the environment and energy consumption. If this step will follow by the industries, it is approximately 1.60 kg CO2 equivalent and 0.52 kg fuel equivalent of environmental benefits and energy resources benefits can avail. The other important material like tellurium, semiconductor and glass output if used as primary product the huge burden can be diminish by industries. Therefore, the usage of secondary material as primary material is high recommended for promoting the achievement by using the less resources and low energy.

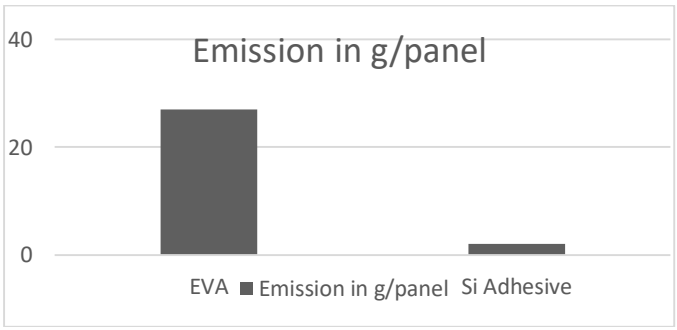

Figure III-6: Emission due to Panel assembly

B. Midstream Process

The midstream process includes the installation of the solar grid, their operation and then retirement. All these process are accounted in term of the energy consumption, emission and the payback period. The resulted data are taken under consideration of different factor like the energy consumed by solar panel during the installation, their transportation, transmission and other components involving. These results are taken from the 67 kW of solar station installed in English biscuit company in Haripur. They had installed two arrays of module. One includes the 560 panels of polycrystalline while the other has 650 panels. The total panels were 1210 in number. Each panel has 250 watts of capacity. The real time data are used in GaBi software and result the different data. The figure III-7 shows the energy consumption by installation monocrystalline and polycrystalline photovoltaic panels of 250 watts of each panel. Which shows the monocrystalline consumed more energy than polycrystalline. The monocrystalline consumed 2810.4 GJ of energy per 67 kW of solar system while the polycrystalline consumed 2215.49 GJ.

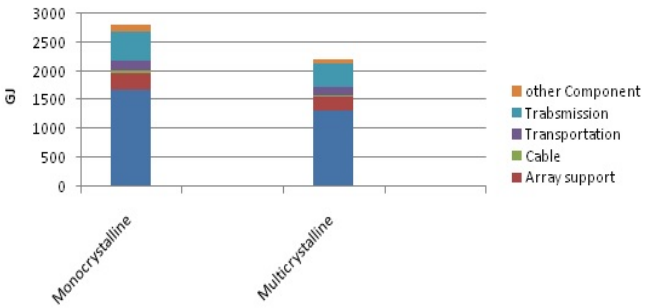

Figure III-7: Energy requirements for small scale PV system (GJ / kW)

The figure III-8 shows the CO2 emission of mono versus polycrystalline of solar panels which again show the monocrystalline have emission then polycrystalline. The high emission includes the 153.64 ton of CO2 eq from the 67 kW of solar system, while the polycrystalline have 128.8 ton of CO2 eq.

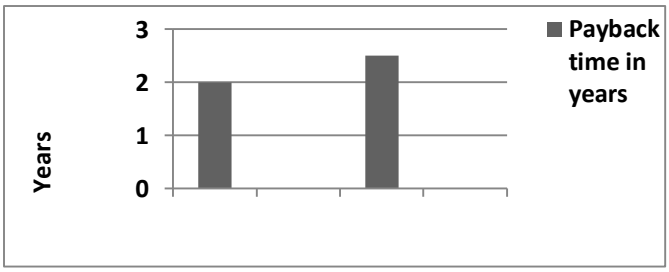

Figure III-8: C02 emission of PV system (t-CO2 / kW)

The figure III-9 shows the payback period of monocrystalline has 2 years while the polycrystalline have 2.5 years. Here it shows the monocrystalline has lower pay back period than polycrystalline. It because of mono has higher efficiency than polycrystalline solar panels. The monocrystalline exists in 17 to 18% efficiency in market but the polycrystalline have 16 to 17%.

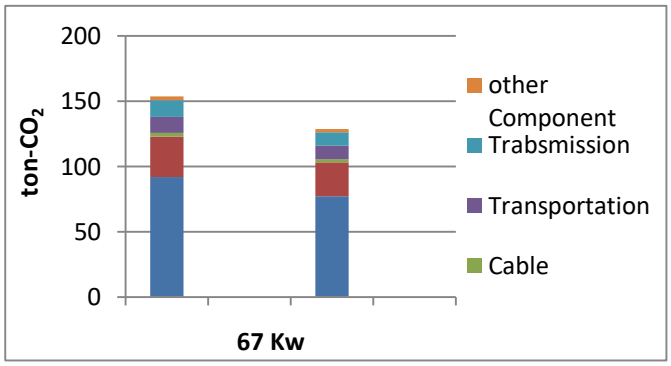

Figure III-9: Payback period of Solar PV system (Years)

C. Downstream Process

The downstream process includes the retirement and decommissioning of the solar modules.There are some of the investigation and results found on the recycling and decommissioning of the solar system. One of the major problem faced by solar industry is the separation of stratify module, because of the polymers linked cross sectional. The industries yet found the solution to dismantle the solar module and reused some part of it in the solar module production. One of the solar companies found the liberation method of wafers and reused them. This method includes the dipping of module in NHO3 for 25 hours. The wafers extracted from this method are then passed with special process and prepare it for moderate performance. But this method is costly than the normal wafer production. The solar cells produced by such method described above are efficient or not, it is not cleared yet or silicon wafer need to re-melt by casting and sawing method. In such cases the energy required to reproduced and separate the silicon by casting and sawing method which tend to increase in the cost per module. But from the results it has found that the aluminum frame can be reuse in the module production.

D. Impact Assessment

The figure III-10 shows below the most significant impacts and results from output of toxic material and their contribution to human toxicity, marine system damaging, and metal resources depletion. The most momentous materials which contribute in human body damaging are Pb (lead), As (arsenic), and Hg (mercury) to air, it causes the bladder and lung cancer by respiratory system in human and animals. The other reports also showed that the skin changes due to Ag (silver) paste, producing glass and electricity. Similarly, the marine ecosystem damages due to copper and nickel to water and air, these substances are mainly produce from Ag pastes and glass. The metal resources depletion is caused by the Ag paste producing method. It gives the dominant contribution in metal depletions. The reduction in cultivated land is the main impact of the larger solar system installation. The average land required for 1 MW solar system is 5-6 acre of land. The results show the output substances contribute about 80% of the ozone layer depletion; these substances will be taken equivalent to the CFCs. The recent researches showed the 2,25x108 kg CFC-11 eq/ kWh.

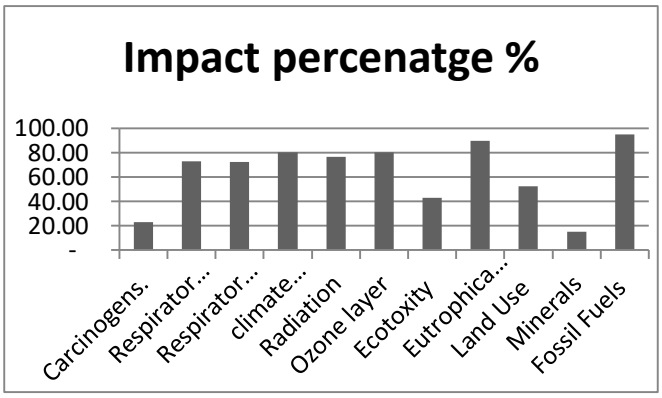

Figure III-10: impact percentage on the environment

CONCLUSION

During the manufacturing of solar panels, the major emissions are occurring due to the energy get from fossil fuels, for manufacturing different components and taking the different operation. these emissions depend on the country, because each country have different energy mix, so the different country have different emission. Briefly the analysis and assumption resulted that the total gross energy requirement (GER) for one solar panel is 1416 MJ /panel and about 79 kg of equivalent CO2/panel generated. And Pakistan can sustain such amount of emission because according to the national GHG inventory of Pakistan for the total GHG emissions annually is 369 MtCO2e with 45.9% part of energy, 44.8% agriculture and livestock sector and the rest contribute the other parts while china who is the largest contributor in global warming produce 7.3 Gton of CO2 annually just from coal. By comparing these two countries we can conclude, Pakistan should start their own manufacturing of solar module. For calculating the energy payback period, it is assumed Pakistan produces 200 panels of 350 watts per day. So it will consume 283 GJ/panels on average. So the EPBT will be about 2-3 years. The most censorious phase in the solar manufacturing is transformation of mg-silicon into sg-silicon and the assembling of panels. Moreover, its estimated that energy payback time would be shorter than the panel life spans. According to researcher survey it had been found that the multicrystalline solar panels are best-selling solar panels in Pakistan. Multi-Si PV system has slightly low efficiency then Mono-Si system, but their energy consumption is less than mono-crystalline. Pakistan has abundant of solar raw material resources, it need to be utilize and take advantage because of energy crises and CO2 emission caused by electricity generation in Pakistan by other non-renewable sources. Therefore, multicrystalline should take in account for manufacturing in Pakistan. Moreover, there are millions of solar panels installed in Pakistan in residential area and non-residential area. There number of these panels are not yet clarified but after 20 and 30 years. These panels will be considering as burden over in pace

of wastes product. These wasted panels can be reuse as secondary product.

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