Sustainability Assessment for Semi-automated Solar Panels Production Facility

Ahmed Fawzi[1], Amna Ramzy[2]

Abstract: This research work demonstrates the potential of material and energy flow analysis (MEFA) digital tool to address sustainability concerns in Semi-automated production lines in SMEs. The paper presents the application of MEFA on a solar panels' assembly facility in the MENA region. The importance of thorough data collection is highlighted as it allows for accurate mapping of how materials and energy are flowing through a system especially in case of manual assembly lines. The challenges in data acquisition are addressed and the improvement scenarios are presented by using simple innovative methods such as QR codes to streamline the data collection process, saving time and reducing errors. Overall, this paper demonstrates how material and energy flow modelling can be used to identify areas for improvement in sustainability practices in small and medium enterprises using simple digital tools.

Keywords: sustainability, digital tools, material and energy flow analysis, solar energy, MENA region.

1 Introduction

Sustaining a healthy life has become a major concern nowadays as a result of the increased awareness about the important environmental threats such as water, resources scarcity and greenhouse gases [Mc17]. Sustainable development was first defined by Brundtland in 1987 to be the development that imposes no irreparable damage to the environment [Br87]. Brundtland also associated the term "Sustainability" with "Industry/Manufacturing" since the industrial practices have direct impact on the environment. Thanks to the revised international policies, the industrial efficiency concept has now changed its concept from "economic efficiency -based" which neglects the environmental impacts of the product, into "Product Performance -based" i.e., considering the environmental aspects. [Ma22]. Despite the recent technological advancements, energy management stays a challenge for SMEs due to the lack of application of smart digital tools and methodologies and the specialists who can perform such analysis and come with practical and efficient solutions [Ri79]. Environmental Management which incorporates materials and energy flows and cost accounting follow known ISO standards

[1] Department of engineering Design and Production, Faculty of Engineering and Materials Science, German University in Cairo, Egypt
[2] Department of Materials Engineering, Faculty of Engineering and Materials Science, German University in Cairo, Egypt

such as ISO 14053:2021 and ISO 50001 [Ha11]. Material and energy flow analysis (MEFA) is a comprehensive tool that can be used by small and medium-sized enterprises (SMEs) to optimize their production processes. This tool provides a holistic approach to identify opportunities for improvements in the energy and material flows within the SMEs production system that might otherwise be too complex or costly to analyze. In addition to supporting sustainability initiatives within SMEs by quantifying the environmental impact of the production process, SMEs can identify areas for improvement and take measures to reduce their carbon footprint by switching to renewable energy sources or implementing waste reduction measures [Ra23].
In order to be able to contain the several variables, inputs and outputs in the whole facility under study, simulation became an indispensable set of technological tools and methods since it allows for experimenting and validating of products, processes, and system design configuration without interrupting the current flow of materials. In other words, for successfully implementing digital manufacturing and production continuity professional simulation tools have to be applied. A growing number of SMEs are turning to MEFA as a key resource to optimize their production processes [Ra22] The reason behind this trend is because SMEs often face challenges such as limited budgets, tight schedules, and reduced resources, which make it challenging to implement large-scale improvements. However, by using MEFA, SMEs can achieve significant improvements with minimal investment. MEFA can help SMEs to identify inefficiencies in their production processes, improve productivity, and reduce operating costs. In addition, MEFA can also help SMEs identify environmental issues and address them proactively, enhancing their environmental sustainability. [Ra21]

Aligning with the global SDGs, the conventional energy sources are shifting swiftly to green energy from renewable sources such as water and solar energy. Despite their low efficiency, photovoltaic technologies have reached nowadays technological maturity and have become the main pillar in green energy technologies mainly in sunny regions such as MENA region [Su16].

This research work investigates the production sustainability for a semi-automated Photovoltaic Panels production Facility in Egypt. The assessment is based on performing the Material and energy flow analysis of the production process and calculating the total energy consumption, waste and carbon footprint. Challenges in data acquisition are discussed and recommendation for improvement of the material and energy data collection in a simple and technician friendly way are presented.

2 Methodology

2.1 Case review

The facility chosen for the case study is a solar panel assembly line. The case was chosen to address the lack of applications in the field. The system boundary is the facility grounds where raw materials are assembled to produce 2 grades of solar panels A & B. MEFA is conducted to visualize and analyze the consumption of resources while recommending possible scenarios to improve efficiency and reduce emissions.

2.2 2.2 Mapping

The process of MEFA begins with mapping out the production process, from raw materials to finished goods, and identifying the inputs and outputs of each step. These inputs and outputs include raw materials, energy, labour, products, waste, and emissions. Once the inputs and outputs of the production process have been identified, the next step is to develop a model that maps out the flow of materials and energy through the system. The model can then be used to perform calculations and predictions.

The study began by contacting the facility and scheduling an initial visit to tour the facility chosen for the application. The following block diagram illustrates the process of the solar panels assembly.

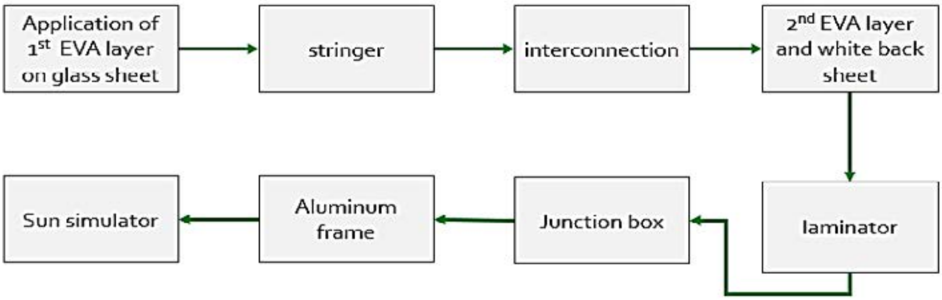

Figure 1: Assembly line block diagram

2.3 2.2 Processes Description

Assembly starts by applying an Ethyl Vinyl Acetate (EVA) layer on top of a 2 by 1 meter glass panel forming a stage one product. In another process solar cells are being inserted into the Stringer machine along with Stringer rolls which are used to connect groups of 12 cells to form a column. The next process takes stage one product and the columns created from the Stringer and lays 6 columns on each product. After that the columns are welded together in a process called interconnection and producing stage three products. After the columns are welded another layer of Eva and a back sheet layer are applied forming the stage 4 product. The stage 4 product is input into the laminator well the Eva layers are melted and the sheets are laminated together forming stage five product inspection takes place after the product exits the laminator and in every 1600 panels Four panels were rejected these were 100% waste and are usually broken the stage five product is then moved to the junction box installation process the junction box is fitted and excess wires are cut off producing the stage 6 product. The stage six product is then fitted with an aluminum frame to hold the integrity of the panel and avoid crack initiation and propagation through the panel through accidental collisions with the glass edges the stage seven product then enters the sun simulator well the voltage produced is tested and a grade is assigned to the panel in every 1600 panels 33 panels are assigned grade B and the rest are grade A products. The inputs and outputs of each process were analyzed, and the ratios of material flow were recorded for modelling.

2.4 2.3 Energy Flows:

The source of energy is a diesel generator, and the average daily consumption is 205 litres per 6-hour shift. The efficiency of the generator is taken to be 40%. The energy content per litre of fuel is taken to be 37MJ/l. The daily energy consumption was calculated as follows:

$$0.4 * 37 * 205 = 3034 \text{ MJ} = 842.7 \text{ KWh} \quad \text{(Equation 1)}$$

Since there were no devices or techniques applied to collect actual consumption data the line was divided into three stages the pre lamination stage lamination stage and the post lamination stage the operation time of each stage was observed and approximated for calculations.Data on the power rating of the equipment was collected from the paperwork and the following data was calculated in Tab. 1 and 2.

Production Stage	Process	Machine Power [KW]	Time of operation [h]	Energy Consumed [KWh]	Energy consumed per panel [KWh/panel]
Pre-lamination	Stringer	40	4	120	2
	Interconnection	0.42	4	1.68	0.028
Lamination	Laminator	175	2	350	5.83
Post-lamination	Frame	3	4	12	0.2
	Sun-simulator	1.76	4	7.04	0.11
Pneumatic	Compressors	59.2	6	355.2	5.92
				845.92	**14.098**

Tab. 1: calculated energy consumption of each process

Pneumatic energy distribution		
T2	EVA layer / layer 1	0.9867
T4	Interconnection	0.9867
T5	EVA bottom + back sheet	0.9867
T10	Junction box installation	0.9867
T11	Aluminum Frame	0.9867
T12	Packaging	0.9867
6 processes consume 5.2 KWh per panel		

Tab. 2: Pneumatic energy distribution

Note: The source of the pneumatic energy are two compressors each rate at 37Kw and an efficiency of 80%.

3 Mapping and Modelling

Using the data collected and with the aid of the process block diagram, a map of the line was created, and the processes were modeled defining the input/ output materials and their flow ratios.

4 Results and Analysis

After modelling the line, the software performed calculations of total flows for the modelled daily production batch of 60 panels and yielded results and analytics including tables showing consumption and loss quantities as well as Sankey diagrams showing the flows with arrows that are proportional to flow quantities and calculated the carbon footprint of the facility for such run.

Figure 2 shows the qualitative material and energy flows where the thickness of the lines resemble the quantity of flow. It is obvious the main energy consuming process is the T6: Laminator which is due to the heat energy required to perfrom the lamination.

Quantitative flows are material and energy flows calculated by the software and illustrated in Figure 2.

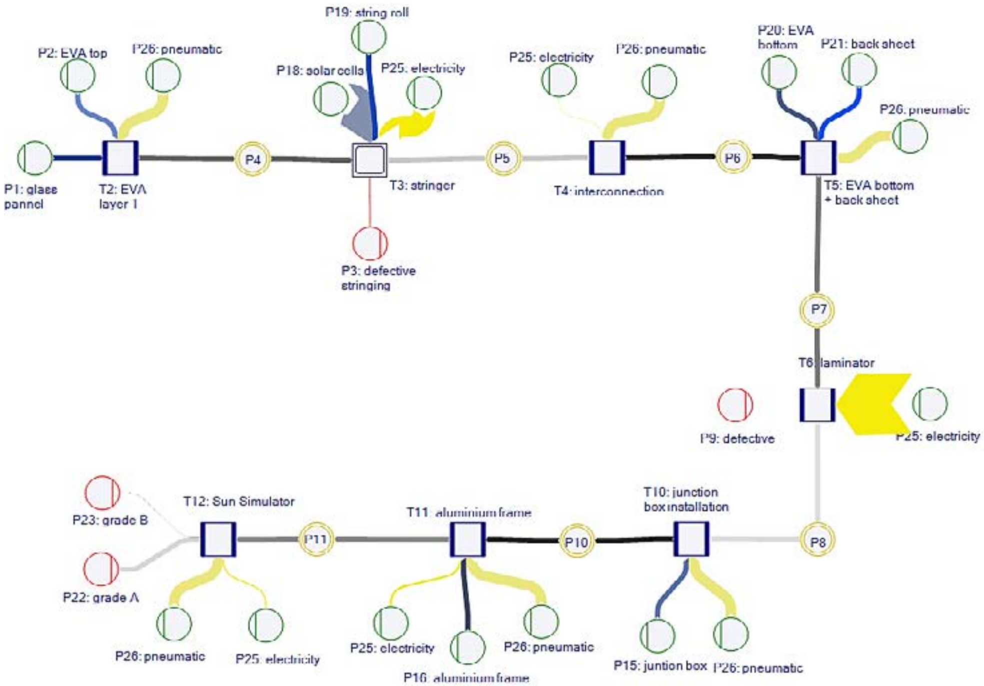

Figure 2: Sankey diagram for the main net

Energy flow calculations are corresponding to the CO_2 emissions estimation for each process where the environmental impact can be assessed accordingly. Emissions for product A are displayed in Figure 3.

By analyzing the results, it can be deduced that material losses are minimal due to the nature of the production line being an assembly line. The carbon emissions results comply with the energy consumption results and show that the process T6: Laminator is responsible for more than 90% of the emissions of the whole assembly line. Taking into consideration that the energy source of the facility is a diesel generator which results in a high carbon emissions from a supposedly sustainable product.

A study published in the journal Nature Energy in 2020 [Vo23] estimated the average carbon footprint of solar panel manufacturing to be around 20-40 grams of CO2-equivalent per kilowatt-hour (g CO2e/kWh) of electricity generated over the panel's lifetime.

Since grade A produces 525 kg for 60 panels then the carbon footprint per panel is 8.75 kg of CO_2 per panel

The average sunlight hours in Cairo, Egypt is 5.62 hours/ day. [Eg23]

$$8.75/(5.62*365*20*0.4) = 0.533 \text{ g } CO_2 / \text{KWh} \quad \text{(Equation 2)}$$

However, the data is not comparable as the study doesn't specify the carbon footprint of the assembly part of the production only as shown in figures 3 and 4.

Product A

Product: grade A [A39 (T12 -> P22)] (58.64 unit)		
LCIA Method: IPCC 2013 - climate change, GWP 100a: 522.47 kg CO2-Eq		
Material: electricity: 303.35 kg CO2-Eq		
T6: laminator	216.29	kg CO2-Eq
T3: stringer	74.34	kg CO2-Eq
T11: aluminium frame	7.42	kg CO2-Eq
T12: Sun Simulator	4.26	kg CO2-Eq
T4: interconnection	1.04	kg CO2-Eq
Material: pneumatic: 219.11 kg CO2-Eq		
T2: EVA layer 1	36.69	kg CO2-Eq
T4: interconnection	36.69	kg CO2-Eq
T5: EVA bottom + back sheet	36.69	kg CO2-Eq
T10: junction box installation	36.60	kg CO2-Eq
T11: aluminium frame	36.60	kg CO2-Eq
T12: Sun Simulator	35.86	kg CO2-Eq

Figure 3: carbon emissions by process in KG-CO2 for product A

Product ***B***

Product: grade B [A43 (T12 -> P23)] (1.21 unit)		
LCIA Method: IPCC 2013 - climate change, GWP 100a: 10.78 kg CO2-Eq		
Material: electricity: 6.26 kg CO2-Eq		
T6: laminator	4.46	kg CO2-Eq
T3: stringer	1.53	kg CO2-Eq
T11: aluminium frame	0.15	kg CO2-Eq
T12: Sun Simulator	0.09	kg CO2-Eq
T4: interconnection	0.02	kg CO2-Eq
Material: pneumatic: 4.52 kg CO2-Eq		
T2: EVA layer 1	0.76	kg CO2-Eq
T4: interconnection	0.76	kg CO2-Eq
T5: EVA bottom + back sheet	0.76	kg CO2-Eq
T10: junction box installation	0.75	kg CO2-Eq
T11: aluminium frame	0.75	kg CO2-Eq
T12: Sun Simulator	0.74	kg CO2-Eq

Figure 2: Carbon emissions by process in KG-CO2 for product B

5 Limitations

The main limitation of this study is the lack of data availability and accuracy. Data was averaged based on memory of the operators only few data sets were logged which results in and inaccurate estimation that may vary from the actual consumption values.

Energy consumption was estimated as total energy consumption without taking the load factor into consideration. Measurements required for the proper calculation of the load factor was unavailable and required a longer time frame than available. This consequently resulted in a limitation of the extent of energy analysis to the total amounts rather than enabling the analysis of the consumption at different load values.

6 Recommendations

6.1 Conversion to solar power

It was noticed that the main source of energy of the facility was a diesel generator. The emissions generated could be significantly reduced by switching to solar energy which logic being its own product.

As mentioned in an earlier calculation, the generator provides a daily supply of 843KW. The panels produced by the facility will be used. Each panel is rated at 0.4 KWh. The average sunlight hours in Cairo, Egypt is 5.62 hours/ day [Eg23]. To meet the facilities, demand the number of solar panels needed is calculated as follows:

*(Daily consumption)/ (number of sunlight hours * energy production per hour)*

$$= (843)/\ (5.62*0.4) = 375 \qquad \text{(Equation 3)}$$

Therefore 375 panels will be required.

Since each panel covers 2m^2 the estimated area required to setup the panel is: $375 * 2 = 750\ m^2$

Carbon footprint after rerun of the model amounted to 0 kg CO_2 / panel taking into consideration the scope of the assembly facility and excluding the LCA analysis.

6.2 Using switches

It was also noted that some electrical equipment was left operating to avoid confusion among the workers. It is proposed that switches are installed to automatically control the equipment and avoid unwanted operation time and cost. Automating the power controls for these equipment would remove the hassle and save the wasted energy.

6.3 Data collection systemization

The data collection recommendation includes:

- QR codes for instant data logging of material consumption and losses
- Paired with an automated logging and analysis tool for electricity consumption.

QR codes can be used to log the data of material losses and energy consumption from the meters by redirecting to a link of a previously developed google form that contains the data fields required to be collected. The technique requires minimal investment and does not require profession. The data collected is logged into a google sheets file where calculation averages and time stamps of the collected data will be available, the data availability will make the data collection easier as well as allow for chart representations of the data to make better predictions and estimations.

The QR codes can then be paired with energy monitoring power meters available for purchase at relatively cheap cost with a variety of optional and features such as mobile apps plots of Realtime usage and wireless monitoring capabilities to be able to access the data anywhere within the facility. The monitoring devices are easily fitted to the main panel and the equipment labelled on the software for easy interpretation of the results.

7 Conclusion:

Material and energy flow analysis is a powerful tool that could be more efficient in applications where high material flow rate and processing is required. However even in cases where flow rates are low it has proved to be beneficial especially for small and medium enterprises through visualization and testing the limitations of the present data collection methods. This process improves awareness of consumption rates and dark spots that can limit the usability and accuracy of the collected data which in turn helps in encourage a more sustainable business culture in SMEs. In the facility being assessed the analysis has shined the light on areas where significant improvements can be made. Such as the conversion of the energy source from a diesel generator to solar power almost eliminating 525kg of daily harmful emissions from a green product (the solar panel) hence improving its contribution to achieving sustainability. Through the application the data collection crisis was highlighted and room for improvement was explored which resulted in the formulation of a feasible and efficient data collection method for the facility. Contributing to more informed and aware business decisions through the analysis of the readily available data in the form of excel sheets where the data can be plotted and averaged to be used in MEFA of other types of analysis hence opening doors for the integration of more analysis variables and preparing our enterprises for the 4th industrial revolution, a data revolution.

8 Outlook:

- Applying the proposed recommendations and testing their effectiveness. Performing of LCA analysis
- Integrate process time, cost analysis, and other key analysis variables such as energy payback time into the analysis.
- Automation of the data collection process in the light of the 4th industrial revolution

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