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Life Cycle Assessment Projection of Photovoltaic Cells: A Case Study on Energy Demand of Quantum Wire Based Photovoltaic Technology Research

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Life Cycle Assessment Projection of Photovoltaic Cells: A Case Study on Energy Demand of Quantum Wire Based Photovoltaic Technology Research
Life Cycle Assessment Projection of Photovoltaic Cells: 
A Case Study on Energy Demand of Quantum Wire Based Photovoltaic Technology Research

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Microelectronics-Photonics

by

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Abstract

With increasing clean-energy demand, photovoltaic (PV) technologies have gained attention as potential long-term alternative to fossil fuel energy. However, PV research and manufacture still utilize fossil fuel-powered grid electricity. With continuous enhancement of solar conversion efficiency, it is imperative to assess whether overall life cycle efficiency is also being enhanced. Many new-material PV technologies are still in their research phase, and life cycle analyses of these technologies have not yet been performed. For best results, grid dependency must be minimized for PV research, and this can be accomplished by an analytical instrument called Life Cycle Assessment (LCA).

LCA is the study of environmental impacts of a product throughout its life cycle. While there are some non-recoverable costs of research, energy is precious, and the PV research community should be aware of its energy consumption. LCA can help identify options for energy conservation through process optimization.

A case study was conducted on the energy demand of a test-bed emerging PV technology using life cycle assessment methodology. The test-bed system chosen for this study was a new-material PV cell. The objective was to quantify the total energy demand for the research phase of the test-bed solar cell’s life cycle. The objective was accomplished by collecting primary data on energy consumption for each process in the development of this solar cell. It was found that 937 kWh of energy was consumed for performing research on a single sample of the solar cell. For comparison, this energy consumption is 83% of Arkansas’s average monthly residential electricity consumption. Life cycle inventory analysis showed that heating, ventilation, and air conditioning consumed the bulk of the energy of research.
It is to be noted that the processes studied as part of the solar cell test-bed system are representative of a research process only. Life cycle thinking can identify energy hot-spots and help a new lab be set up in a more energy-efficient way. Proactive action based on the results can lead to higher energy return on investment, making emerging PV technologies truly energy-competitive.
Acknowledgements

The inception of this project was a result of my advisor Dr. Ajay P. Malshe’s vision for life cycle analysis of solar cells. I am grateful for the opportunity to conduct this research for my master’s thesis and for Dr. Malshe’s guidance.

I would like to thank Dr. Gregory Salamo and his team for their contribution to this project. This project would not be possible without an engineering test-bed vehicle, provided by Dr. Salamo, and data contribution from members of his research group. The main person for communication regarding the test-bed system was Mr. Colin Furrow, PhD student. Other members who contributed data to this project include Mr. Dave Monk, Dr. Vitaliy Dorogan, Dr. Andrian Kuchuk, Dr. Mike Hawkridge, Dr. Vasyl Kunets, and Dr. David Fuller.

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Dedication

This thesis is dedicated to conservative energy research

because kWh is the currency of the future
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List of Abbreviations

LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
ISO: International Organization for Standardization
PV: Photovoltaic
HVAC: Heating, Ventilation, and Air Conditioning
GWP: Global Warming Potential
MBE: Molecular Beam Epitaxy
IP: Intellectual Property
UA: University of Arkansas
TWh: Tera watt hour ($1 \times 10^{12}$ watt-hour)
LCIA: Life cycle impact assessment
CHAPTER 1: INTRODUCTION

Flint Creek, the coal-fired power plant that supplies electricity to most of the Northwest Arkansas area in the United States, emits more than 2000 lbs of CO$_2$ per MWh of electricity generated. With an annual generation of 3.6 TWh of electricity, that translates to 3.9 million tons of annual CO$_2$ emissions [1]. The heavy environmental burden of CO$_2$ emissions are directly related to global warming. Environment protection is one of the key factors that has propelled the world toward clean-energy research.

1.1 MOTIVATION FACTORS

1.1.1 Energy supply-demand imbalance

Energy needs are supplied by different sources. Figure 1 shows the growing energy demand over the years in the U.S. [2].

![History of energy consumption in the United States (1776-2012)](image)

Figure 1: Growth of energy demand and dependency on different types of fuels [2].

World energy demands are supplied by different types of energy sources, as shown in Table 1 [3].
Table 1: Energy available from various sources [3].

<table>
<thead>
<tr>
<th>Renewable</th>
<th>Source</th>
<th>TWy per year</th>
<th>Finite</th>
<th>Source</th>
<th>TWy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ocean thermal [9]</td>
<td>3 – 11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wind [5]</td>
<td>60 – 120</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solar [5]</td>
<td>23,000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is clear that non-renewable supplies are limited and depleting (Table 1). At the same time, world energy demand is increasing (Figure 1). To meet this need, it is imperative to make a
strong move toward renewable energy sources. With increasing energy demand (world energy use averages ~16TWy per year [3]) and decreasing non-renewable resources, photovoltaic (PV) technologies have gained attention as potential long-term alternative to fossil fuel energy, because solar energy is in abundance and freely available.

1.1.2 PV research expenditure

While PV research is ubiquitous in the United States, PV manufacturing and utilization are not, as is obvious from Figure 1. Figure 2 shows the energy consumption distribution in the US as of 2013 [10].

![Energy consumption distribution in U.S. (2013 data)](image)

**Figure 2: Energy consumption distribution in U.S. (2013 data)** [10].

The National Science Foundation has awarded $0.7 billion in PV research to date and $46.7 million for PV projects that started in 2014 [11]. However, the PV market today is owned by China with Germany as a close second [12], [13]. This disparity not only presents an economic sustainability issue for the solar industry in the US, but also presents concerns over poor environmental regulations of the booming solar industry in China.
1.1.3 PV Market and environmental regulation policies

Environmental regulation policies in China are not evolving along with the expanding solar market. Carbon footprint is a big issue since solar panel manufacturing factories use coal-fired electricity for their operations [14]. Figure 3 and Figure 4 compare the energy payback time and carbon footprint respectively for solar panel manufacturing in China (CN) and Europe (RER) [15].

![Figure 3: Energy payback time (EPBT) of solar panel manufacturing in China and Europe [15].](image)

![Figure 4: Carbon footprints of solar panel manufacturing in China and Europe [15].](image)
European solar industry’s carbon footprint is lower than that of China’s since almost half of the grid electricity used for the solar industry is generated from renewable energy sources, like wind and solar energy. The other half is supplied from non-renewable energy sources. It is clear that for a truly clean energy pursuit, multiple aspects of solar power generation must be assessed, including manufacturing processes of solar-powered devices.

1.1.4 Solar cell life cycle

In the US, PV research is thriving and scientists are pushing the cap on conversion efficiency. Highest efficiency recorded by the National Renewable Energy Lab so far is 44.4% conversion efficiency for a triple junction concentrator PV cell [16]. But it is worth noting that PV research utilizes grid electricity, most of which is sourced from fossil fuels in the US. This presents a paradox. The difficult question to be answered is: What is the parasitic energy demand for researching solar cells? With continuous enhancement of solar conversion efficiency, it is imperative to assess whether the overall life cycle efficiency is also being enhanced.

Life cycle thinking is important in order to assess the viability of PV becoming the world-wide utility-scale alternative to coal. Installation capacities are already growing (as can be extrapolated by the graph in Figure 5) [17]. This growth presents further concerns: Has an infrastructure been established for dealing with the cells installed before year 2006, which are approaching their end-of-life? Or is their grave a landfill? Where do the solar cells come from and where do they go? It is imperative to address these not-so-frequently-asked questions in order to assess whether solar cells are really our utility-scale energy alternative for the future. In order to address the above concerns, a holistic and unbiased analytical approach must be used that incorporates the life cycle of the technology. Life cycle of a device includes raw-material
acquisition, material processing, device fabrication, device packaging, transportation, utilization, and final disposal or recycling.

Figure 5: Growing PV installation capacity [17].

Figure 6 shows the life cycle of a crystalline silicon (c-Si) solar cell. The life cycle of a c-Si solar cell involves quartz extraction, Si purification, wafer-manufacturing, transportation, solar cell device fabrication, packaging, panel building, and transportation to site, installation, utilization, decommissioning, and disposal. The utilization phase involves balance of system such as lead-acid batteries, wires, and micro-inverters. The disposal phase involves recycling, incineration, or land-filling. Transportation is usually the most energy intensive stage in the life cycle. Recycling processes are also energy intensive as it is extremely difficult to separate materials packaged into a solar cell. Incineration and land filling are burdensome to the environment. Energy conversion and storage are the only life cycle stages where one may expect energy generation to outdo the parasitic energy demand. It is clear that analysis of a product’s entire life cycle can give a more holistic view of a product’s true potential.
Figure 6: Life cycle of a c-Si PV module.

Silicon PV is a mature technology. It is already in the market and industrial processes are being optimized to save energy. Attention is to be focused on those technologies that are still in the research phase of their life cycle so that an industrial foresight can be gained on how to best manufacture the cells before they are ready to be commercialized.

Gaining industrial foresight by assessing the research phase of the life cycle of an emerging PV technology was the main motivation behind this project. Action based on the results of such life cycle analyses would lead to environmental sustainability and a healthier economic cycle for PV technologies.
1.2 LOGICAL APPROACH TO ANSWER THE ENERGY QUESTIONS

1.2.1 The requirement

Energy in the form of electricity is easily transmitted, distributed, and used, and we know that coal is the most widely used fuel for utility-scale electricity generation. Coal combustion is also one of the most polluting sources of electricity generation with high CO_2 emission/MWh. Hence, it is obvious that we must either reduce coal powered electricity consumption, or use an alternate approach to generate electricity if we want to protect the environment.

Photovoltaic energy conversion is a clean process. Solar energy is freely available and in abundance (renewable) whenever the sun is shining. Therefore, photovoltaic energy generation can be an alternate to coal powered energy generation. But manufacturing solar cells utilizes grid electricity, which, as stated before, relies heavily on fossil fuels. Therefore, in order to assess whether PV energy generation is a viable alternative to coal powered generation, the energy consumption for PV cell manufacture must be quantified and minimized to make PV technologies energy effective.

1.2.2 The tool

Life cycle is the consecutive and interlinked stages of a product system. A product system is the collection of unit processes that model the life cycle of a product. A product can be any goods or service [18]. By this, a photovoltaic cell is a product and the processes that model the life cycle of a PV cell constitute the product system of the PV cell. Life Cycle Assessment (LCA), in general, is the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle [18]. LCA of a PV cell system, in particular, is the compilation and evaluation of I/O and potential environmental impacts of the PV cell system throughout its life cycle.
1.2.3 The metric

Life cycle assessment is an impact assessment tool. As such, there are many impact categories that LCA can cater to. Global warming potential, eutrophication, acidification, ozone depletion and eco-toxicity are some examples of impact categories. Cumulative energy demand (the total energy consumed by a product system) is also an impact category, but it is less commonly used. An LCA with cumulative energy demand (CED) as the impact category can be used to quantify the energy consumption for manufacturing PV cells. CED can then be compared to energy generated by the PV cell to check for viability of the PV technology as an alternative to coal.

LCA’s unit process methodology can give a detailed breakdown of energy consumption by each unit process. The breakdown of energy consumption will reveal energy hotspots in the PV cell system. Energy hotspots are opportunities for significant CED reduction, thus increasing effective energy efficiency of the system.

1.2.4 The implementation

There are different PV technologies existing in the market. Ex. Silicon, II-VI, III-V, Organic, Dye Sensitized, etc. Life cycle processes for a product cannot be easily modified once the product is being mass manufactured as its life cycle processes would already be established by manufacturer and consumer practices. Assessing viability of existing technologies will not affect much change in the environmental impact of the system. But an LCA performed at the design stage can help implement better (more energy efficient) processes at the manufacturing stage. Therefore, an emerging technology must be selected as the subject of this study because these are the technologies that are still in the design and prototype stage, and have not been mass
manufactured yet. Thus a positive change in environmental impact can be expected after LCA is performed on an emerging PV technology.
CHAPTER 2: LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

2.1 BACKGROUND

The International Standard Organization (ISO) has defined methodology for performing a life cycle assessment study. The definition of LCA as per the ISO is as follows [18], [19]:

“LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product’s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave).”

Figure 7 [20] shows the generic life cycle of a generic product.

Table 2 is a list of the ISO documents that address LCA methodologies [21].

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Title</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>14041</td>
<td>International Standard</td>
<td>Goal and Scope Definition and Inventory Analysis</td>
<td>1998*</td>
</tr>
<tr>
<td>14042</td>
<td>International Standard</td>
<td>Life Cycle Impact Assessment</td>
<td>2000*</td>
</tr>
<tr>
<td>14043</td>
<td>International Standard</td>
<td>Life Cycle Interpretations</td>
<td>2000*</td>
</tr>
<tr>
<td>14044</td>
<td>International Standard</td>
<td>Requirements and Guidelines</td>
<td>2006**</td>
</tr>
<tr>
<td>14047</td>
<td>Technical Report</td>
<td>Examples of Applications of ISO 14042</td>
<td>2003</td>
</tr>
<tr>
<td>14048</td>
<td>Technical Report</td>
<td>Data Documentation Format</td>
<td>2001</td>
</tr>
</tbody>
</table>

* Updated in 2006 and merged into 14044.
** Replaces 14041, 14042, and 14043.
The criteria for performing LCA are enumerated in:

- ISO 14040: Environmental management – Life cycle assessment – Principles and framework
- ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines

These two documents were compiled from the documents listed in Table 2.

Cumulative Energy Demand is one of the environmental impact categories that are addressed as part of an LCA. But to quantify any environmental impact of a product, one must first create a data inventory of all the materials and energy used and emitted for each process within the product system’s life cycle. Overall, LCA is accomplished in four stages as per the ISO standards on conducting LCA. These stages are related as shown in Figure 8 [18], [19].

The four major stages are:

1. Goal and Scope Definition
2. Life Cycle Inventory Analysis
3. Life Cycle Impact Assessment
4. Interpretation

Figure 8: The four stages in LCA [18], [19].
LCA is an iterative process. One may modify or redefine the goal and scope based on limitations in data collection or other similar factors. The inventory may change based on impact categories. All changes must be justified and at all times one must ensure that the inventory and impact assessment stages are as per the goal and scope defined. All the stages are interrelated as shown in Figure 8 and each stage is defined and explained next. Unless otherwise mentioned, the following sections on the four phases of LCA are obtained from ISO 14040 and ISO 14044 [18], [19].

2.1.1 Phase 1: Goal and scope definition

Goal and Scope definition is the first step in an LCA where the practitioner explicitly states the purpose of the study. The application of the results and the audience to whom the results will be shown must also be stated. Other items to be stated include:

- Product system to be studied
- System boundary
- Functional unit
- Types of impacts
- Data quality requirements
- Assumptions and limitations

2.1.1.1 Nomenclature

Product: A product can be any goods or service, tangible or intangible.

Product System: A product system is the collection of unit processes in the life cycle of the product to be studied.

System Boundary: System boundary is the part of the product system that is relevant to the particular study. A generic product system is shown in Figure 9 along with a system boundary
Unit processes that are inside the system boundary are accounted for in the study. Unit processes that fall outside the system boundary are outside the scope of the LCA. The system boundaries must be clearly shown in the scope definition.

Figure 9: Product system and system boundary [18], [19].

**Functional unit:** A functional unit is a unit of performance that is desired from the product that can be used as a reference for comparison of LCA results of products with similar functions. According to ISO 14040, a functional unit is a “quantified performance of a product system for use as a reference unit” [18].

### 2.1.1.2 Data quality requirements

Data quality requirements address the standard of data to be collected for the inventory. Data quality accounts for the following factors:

- Time-related coverage
- Geographical coverage
- Technology coverage
- Completeness
- Reproducibility
- Sources of the data
- Uncertainty of information

These factors show us the relevance of the data collected and aid in making fair comparisons between or among products.

### 2.1.1.3 Types of LCA based on goal

There are two types of LCA based on goal: Attributional and Consequential [22]–[24].

**Attributional LCA:** this type is used to determine the environmental burdens for the production and use of a chosen product.

**Consequential LCA:** this type is used to estimate the response that a decision or a proposed change to the system may have on the environment. This study uses Attributional LCA since there is only one system under consideration with no changes proposed to the system.

### 2.1.1.4 Types of LCA based on scope

There are six types of LCA based on scope of a study [22]–[24]:

1. Cradle to Grave: complete LCA from raw material acquisition to final disposal;
2. Cradle to Gate: from raw material extraction, through processing, assembly, and packaging, to factory gate (before shipping to customer);
3. Cradle to Cradle: product is recycled instead of disposed;
4. Gate to Gate: partial LCA of specialized unit process studies;
5. Well to Wheel: vehicle fuel-cycle analysis;
6. Economic Input-Output LCA: trace aggregate economic value of products for each sector to determine environmental impact.

This study uses Gate to Gate LCA since only the material growth and device fabrication processes are taken into consideration.

**2.1.2 Phase 2: Life cycle inventory analysis**

This is the phase that involves compiling and quantifying inputs and outputs of a product system’s unit processes. This stage involves:

- Data collection
- Data calculation
- Data allocation

This is an iterative process where the first set of data collected may not meet the goal and scope definition. In such a case, either data must be collected again as per the requirements, or the goal and scope must be refined with justifications in terms of assumptions and limitations. To ensure that no data is missing, data will be collected for each unit. A unit process is the “smallest element considered in the life cycle inventory analysis for which input and output data are quantified” [18]. A sample inventory sheet is provided in Figure 10. Since the impact category of interest is Cumulative Energy Demand, energy input is the only factor considered for each unit process.

**2.1.3 Phase 3: Life cycle impact assessment**

LCIA stands for life cycle impact assessment which is “aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” [19]. Steps in LCIA include:

- Selection of impact categories
- Classification
- Characterization
- Evaluation of the significance of potential environmental impacts using inventory results.

There are several impact categories that may be assessed using LCA; for instance, global warming potential, total energy demand, acidification, eco-toxicity, etc. For this study, only one impact category is considered: Total Energy Demand.

2.1.3.1 Classification

Classification is the distinction between different life cycle inventory elements that contribute to various impacts. For instance,
- \( \text{SO}_2 \) assignment to human health and acidification, and
- \( \text{NO}_x \) classification to both ground-level ozone formation and acidification
where \( \text{SO}_2 \) and \( \text{NO}_x \) are life cycle inventory elements, and human health, acidification, and ground-level ozone formation are impacts categories.

2.1.3.2 Characterization

Characterization is the factor by which the inventory elements cause or contribute to environmental impacts. For instance [25]:
- 1g of \( \text{CO}_2 \) has a global warming potential (GWP) of 1.
- 1g of \( \text{CH}_4 \) is equivalent to 21g of \( \text{CO}_2 \). Therefore, 1g of \( \text{CH}_4 \) has a GWP of 24.
- 1g of \( \text{N}_2\text{O} \) = 310g of \( \text{CO}_2 \) equivalent. Therefore, 1g of \( \text{N}_2\text{O} \) has a GWP of 310.
- 1g of \( \text{SF}_6 \) = 23,900g of \( \text{CO}_2 \) equivalent. Therefore, 1g of \( \text{SF}_6 \) has a GWP of 23,900.

According to ISO 14044, the impact assessment phase is fairly subjective as it leaves the choice of impact category up to the discretion of the practitioner, and thus, the assessment needs to be transparent.
Figure 10: Sample inventory sheet [19].
2.1.3.3 Types of LCA based on impact categories

There are three types of LCA based on impact categories: Environmental, Economic, and Social LCA:

- Environmental LCA includes impact categories such as eco-toxicity, global warming potential, energy demand, energy return on investment, energy payback time, acidification, eutrophication, human health, etc.
- Economic LCA is about the effect of a decision on the micro and macro-economics of a product system
- Social LCA includes factors such as customer satisfaction, employee satisfaction, workplace security, career development, poverty, average family income, employment, etc.

This project focuses on Environmental LCA since the impact category of interest is total energy demand.

2.1.4 Phase 4: Interpretation

This is the phase where life cycle inventory and impact assessment results are combined and evaluated with respect to the goal of the LCA in order to arrive at relevant conclusions and recommendations. Certain evaluations help provide more confidence in the LCA results.

Completeness check

- Consider if all data that was stated to be collected, was actually collected
- Evaluate how missing data may affect the results
- Justify exclusions of any data

Sensitivity check

- Consider variability in data collection and how it may affect final results
• Consider expert opinions

Consistency check

• Check if the inventory analysis phase and impact assessment phase are consistent with the goal and scope definition
• Ensure collected data meet data quality requirements. Data quality requirements need to be mentioned in the goal and scope definition section.

2.2 EXAMPLES OF LCA IN THE ENERGY SECTOR

Following are some examples of the significance of LCA in the energy sector.

2.2.1 Example 1: Renewable v. conventional systems

LCA has been used to compare greenhouse gas emissions from renewable and non-renewable energy generation systems. A summary of the quantified equivalent CO₂ emissions for each system is provided in Table 3 [26].

<table>
<thead>
<tr>
<th>Conventional Systems</th>
<th>Renewable Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>g-CO₂/kWh</td>
</tr>
<tr>
<td>Coal fired</td>
<td>975.3</td>
</tr>
<tr>
<td>Oil fired</td>
<td>742.1</td>
</tr>
<tr>
<td>Gas fired</td>
<td>607.6</td>
</tr>
<tr>
<td>Nuclear</td>
<td>24.2</td>
</tr>
<tr>
<td>Hydro</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Greenhouse gas emissions [26].
The LCA analysis showed that while non-renewable energy generation systems were more detrimental to the environment, PV energy systems have been the most polluting among all the renewable sources of energy.

2.2.2 Example 2: Environmental product declaration

Companies use life cycle assessment to leverage their products in the market by labeling them as environmentally friendly. One example is a set of solar controlled windows called Solar Gard that are manufactured by Solar Gard Saint-Gobain. The windows are protective window films for buildings and cars. The Green Standard is the program that provides the certificate and making use of life cycle assessment results to make decisions for product declaration. Declaration number for Solar Gard is TGS-1020914-0512-A. Solar Gard has been proven to reduce greenhouse gas emissions according to LCA results. The LCA methodology is compliant with ISO 14040:2006 (Environmental management – Life cycle assessment – Principles and framework), ISO 14044:2006 (Environmental management – Life cycle assessment – Requirements and guidelines), ISO 14025:2006 (Type III environmental declarations – Principles and procedures), ISO 21930:2007 (Sustainability in building construction – environmental declaration of building products). Details of the methodology used can be found online at the green standard’s website [27].

2.2.3 Example 3: Energy sector-wise human fatalities

Fthenakis, et al. [28] have used life cycle assessment to compare human fatalities across energy sectors. Figure 11 summarizes their results.
**Figure 11:** Maximum fatalities from accidents across energy sectors [28].

This analysis showed that PV technologies are relatively safer than other energy harvesting technologies [28].
CHAPTER 3: LITERATURE REVIEW

3.1 TYPES OF PV TECHNOLOGIES

Different types of solar cells are enumerated on the “best Research-Cell Efficiencies” chart published by NREL each year. This list of solar cells is reproduced here [16]:

- Crystalline silicon cells
  - Single crystal (concentrator)
  - Single crystal (non-concentrator)
  - Multicrystalline
  - Thick Si film
  - Silicon heterostructures
  - Thin film crystal

- Single junction GaAs
  - Single crystal
  - Concentrator
  - Thin-film crystal

- Multijunction cells
  - Two junction (concentrator)
  - Two junction (non-concentrator)
  - Three junction (concentrator)
  - Three junction (non-concentrator)
  - Four junction or more (concentrator)
  - Four junction or more (non-concentrator)

- Thin film technologies
- CIGS (concentrator)
- CIGS (non-concentrator)
- CdTe
- Amorphous Si:H (stabilized)
- Nano-, Micro-, Poly-Si

- Emerging PV
  - Dye-sensitized solar cells
  - Perovskite cells
  - Organic cells (various types)
  - Organic tandem cells
  - Inorganic cells (CZTSSe)
  - Quantum dot cells

Some of these technologies are discussed in the following sections.

### 3.2 EXAMPLES OF LCA OF PV TECHNOLOGIES

Following are examples of life cycle assessment (LCA) results obtained for solar cell technologies studied. Details can be found in the relevant publication referenced.

#### 3.2.1 Example 1: Deutsche Solar’s module recycling process

LCA has been instrumental in Deutsche Solar’s marketing of their crystalline silicon (c-Si) PV module recycling technology. Through a life cycle energy analysis, Deutsche Solar showed the superiority of manufacturing solar cells from recycled materials compared to virgin materials (see Table 4) [29]. According to Deutsche Solar’s analysis, it takes 459 kWh to make cells out of virgin materials, while it takes only 196 kWh to make cells from recycled materials.
Energy payback time for the non-recycled modules is 3.8 years while for those made from recycled wafers is 1.6 years. Other environmental impacts of recycling and thermal-chemical treatment of Deutsche Solar’s modules are displayed in Figure 12 [29].

**Table 4: Life cycle energy analysis of PV modules (160 WP) with recycled wafers compared to non-recycled wafers [29].**

<table>
<thead>
<tr>
<th></th>
<th>With Recycling (kWh/module)</th>
<th>Without Recycling (kWh/module)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer Production</td>
<td>-</td>
<td>355</td>
</tr>
<tr>
<td>Recycling Process</td>
<td>92</td>
<td>-</td>
</tr>
<tr>
<td>Cell Processing</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>Module Assembly</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>196</strong></td>
<td><strong>459</strong></td>
</tr>
</tbody>
</table>

**Figure 12: Impact of Deutsche Solar's module recycling process [29].**
The LCA summarized that disburden (reduction in negative impact) on the environment due to the recycling process is greater than the burden of the recycling process. Clearly, Deutsche Solar’s LCA on energy demand proves the recycling method to be a viable approach to save energy.

3.2.2 Example 2: CdTe v. Si rooftop modules

Greenhouse gas (GHG) emissions were compared for Si and CdTe rooftop modules [28]. It was found that while Si solar modules have a higher efficiency than CdTe modules, Si modules generally contribute more to GHG emissions than CdTe modules. The emission breakdown is provided in Figure 13. It is evident that the module (as opposed to the balance of systems or the frame) is responsible for most of the GHG emissions in both Si and CdTe solar cells. Therefore, LCA was used to make fair comparisons between CdTe and Si technology, and also to compare the different system components in both Si and CdTe modules.

![Figure 13: Impact of Deutsche Solar’s module recycling process][28]
3.2.3 Example 3: Si manufacturing energy demand

CdTe and Si solar cell life cycles were compared. LCA results indicated that the reason for higher energy demand of the Si solar cell comes from the energy requirement of the manufacturing phase of the Si PV module life cycle. The energy used to manufacture Si PV modules is more than the energy used to manufacture CdTe PV modules [28].

3.2.4 Example 4: Panel configurations

Several combinations of solar cell type, panel type, and installation type were studied for cell efficiency. All systems relate to a 3 kWp plant. It was found that maximum surface area was required for amorphous Si solar cells. Mono-crystalline Si solar cells have the highest efficiency among amorphous, polycrystalline, and mono-crystalline solar cells and thus require least surface area among the three for generating the same amount of power. Finally, it was found that monocrystalline Si modules, laminated, and integrated onto a façade can take up maximum energy in its life cycle among the different types studied [30].

3.2.5 Example 5: End-of-life options

LCA can help us evaluate several end-of-life options for PV modules. For instance, recycling solar grade (SoG) Si wastes can save $5.1b/year. However, the recycling process is challenging as PV module materials are tightly packed together and it is difficult to separate them. Some of the more feasible material separation methods include [31]:

- Electromagnetic separation
- Centrifugal separation
- High temperature re-melting
- Bubble floatation
Life cycle analyses of solar cells force us to pre-plan post-decommissioning procedures at an early stage.

3.2.6: Example 6: Energy pay-back time and module cost

Another LCA study of reduction potential of environmental impacts of c-Si PV technology has shown that a decrease in energy payback time and module cost can be attributed to [32]:

- Low Si consumption
- Low energy input in Si feedstock production
- Low Si cost
- High cell efficiency and
- High scale of production

3.2.7 Example 7: Fluidized bed reactor v. Siemens process

An LCA study of Si PV life cycle brought out the differences between Siemens process and Fluidized bed reactor process. Approximately 110 kWh of electricity and 185 MJ of heat are used to produce 1 kg of polysilicon with the Siemens process. The results showed that the cumulative energy demand of the Fluidized bed reactor process was half that of Siemens process. Life cycle greenhouse gas emissions for a multi-crystalline Si solar cell can be reduced from 30 g/kWh to 15 g/kWh or less [32].

3.2.8: Updates

From 2006 to 2009, manufacturing processes have changed in the PV industry and thus the life cycle inventory was updated based on new factors such as improved efficiency, NF3 production and usage, lower EPBT, lower GHG emissions, lower primary energy in general, reduced thickness of wafer, etc. Causes for divergence among several researchers’ analyses were investigated, and the differences in the results were due to differences in the system boundaries,
or assumptions made by the researchers that brought about the divergence [28], [30], [32], [33].

The above analyses were done on both CdTe and Si PV technologies. It indicates that both technologies are progressing toward lower emissions and EPBT. CdTe has better environmental profile compared to Si technologies. However, their efficiencies are not as high and the human safety/human hazard factor has not been analyzed [33].

The few LCA studies available on photovoltaics focus on existing commercial technologies like Silicon, Cadmium telluride, polymer, organic, thin film, Gallium arsenide, etc. These are summarized in Table 5.

**Table 5: Summary of literature review on LCA of PV technologies.**

<table>
<thead>
<tr>
<th>Technologies compared</th>
<th>% of PV LCA literature (approximate)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdTe, Si</td>
<td>10% - 20%</td>
<td>[33]</td>
</tr>
<tr>
<td>Polymer, Organic, Inorganic</td>
<td>5% - 10%</td>
<td>[34]</td>
</tr>
<tr>
<td>Fluidized Bed Reactor vs. Siemens process</td>
<td>10% - 15%</td>
<td>[32]</td>
</tr>
<tr>
<td>CdTe, mono-Si, multi-Si, ribbon-Si</td>
<td>20% - 30%</td>
<td>[28]</td>
</tr>
<tr>
<td>Mono-Si, poly-Si, a-Si</td>
<td>20% - 30%</td>
<td>[30]</td>
</tr>
<tr>
<td>New material based III-V solar cells</td>
<td>None found</td>
<td>NA</td>
</tr>
</tbody>
</table>

As there is no published research on the environmental effects of nano-engineered materials like quantum dots and quantum wires’ incorporation in PV cells, it is prudent to analyze the effects of such emerging technologies before they enter the market. Such industrial foresight at the development stage can identify risks that can be accounted for at the design stage. This master’s level research was an energy demand projection (using LCA methodology)
of nano-engineered PV cell technologies and their development stage in the life cycle as this is of high impact but has never been studied before.

3.3 MOTIVATION FOR CASE STUDY

One of the emerging technologies in PV research and development is PV cells made from nano-engineered materials such as quantum dots, quantum wires, nano rods, etc. One such system, an InGaAs quantum wire intermediate band PV cell has been identified as a test bed subject for this project. LCA of this system can be applied to most other emerging PV technologies that use similar processes for cell growth and development. This has never been done before as indicated in the literature review. Since this technology is within its incubation period, a projection of the unit processes can be made for industrial scale implementation. An LCA of the test bed system can be extrapolated to give a projection of what the assessment would look like if the technology were to be brought to the factory floor. Identifying energy hotspots after scaling up can provide opportunities for reducing total energy consumption significantly for an industrial scale system at the design stage. Such foresight can prevent immense wastage of energy during commercialization. Therefore, an LCA projection of energy demand of a research PV cell system can lead to making the PV cell system a more viable alternative to coal powered electricity generation system. The case selected is also convenient since it is a local project. Thus primary data can be easily obtained for this test-bed system.
CHAPTER 4: TEST-BED SYSTEM FOR THE CASE STUDY

4.1 SYSTEM SELECTION

Nano engineered PV cell materials in III-V solar cells are emerging technologies. Their purpose in a solar cell is to introduce intermediate band gaps in the solar cell material that will capture more of the IR spectrum of sunlight that is generally lost. This is done in order to enhance the efficiency of the solar cell further. A quantum dot or quantum wire PV cell technology thus qualified well as the subject of the study of LCA on emerging PV technology. Other factors considered in selection of the test-bed system are discussed here.

Ease of access to cutting-edge PV technology was one of the deciding factors in test-bed system selection. Research related to nano-engineered quantum dot/quantum wire PV cell materials is performed in research institutes and government labs. Widespread research in this area is difficult as material growth is complex, time-consuming, and expensive. National Renewable Energy Labs (NREL), The University of Toronto, and Massachusetts Institute of Technology (MIT) are the entities that have published their results [16]. The University of Arkansas is currently researching these new materials. Students of one of the research groups at the University of Arkansas’s Institute for Nanoscience and Engineering grow these materials for solar cell and laser applications. The group, led by Dr. Gregory Salamo, has published their investigations [35]. One of their systems, was chosen as the test-bed vehicle for this project. This has proven to be an apt and practical test-bed system for this case study.

The research on quantum dots and quantum wires for PV cells at the University of Arkansas is possible due to the infrastructure available to the scientists and engineers. These nano-scale structures are so small and intricate that they are grown bottom-up. Molecular beam epitaxial growth is the method used for developing these prototypes for research purposes.
Molecular beam epitaxy (MBE) machine is the equipment that is used for these high-precision growths.

Permission was granted for use of the quantum wire based GaAs PV cell system as the subject for this LCA study. The purpose of this study is to benefit the researchers investigating quantum wire growth by helping them identify energy hotspots and providing them an opportunity to increase the effective energy efficiency of the solar cells under study. For ease of access, and for the above-mentioned opportunities, quantum wire based GaAs solar cell development was identified as the test-bed system for this LCA study.

4.2 PROCESS FLOW AND SYSTEM BOUNDARY

The subject matter of the test-bed system is explained in a publication in Applied Physics Letters [35] and the process flow is discussed briefly here. Figure 14 shows the brief overview of the test-bed system and its boundary.

This Gate-to-Gate LCA process flow is captured in its entirety in Figure 15. There are five major steps in the process: material growth, material characterization, fabrication, electronic packaging, and device characterization. These steps are further divided into unit processes which are explained next.
Figure 15: System diagram.
4.2.1 Modeling and simulation

Design parameters for material growth are tested against a simulation before they are physically added on the solar cell device. The only equipment needed for this operation is a computer.

4.2.2 Material growth

The process starts with a 2” diameter GaAs wafer obtained from a manufacturer. This is the starting point (the “gate”) of our LCA (Modeling and simulation is included). The wafer comes doped with silicon. It is then cleaned and cleaved into quarters as shown in Figure 16.

![Initial wafer cleaved into quarters](image)

Figure 16: Initial wafer cleaved into quarters.

Then it is loaded to the degas station which is purged of all other gases using nitrogen gas. This process takes place at 350 °C. Liquid nitrogen (LN2) is filled in a reservoir and the valve to the chamber is opened in order to let the LN2 cool the chamber. Once the chamber is cooled, the cells can start warming up to growth temperatures. Once growth temperature is achieved,
material can be grown on the cell. The growth layers are given in Table 6 [35] and are shown in Figure 17. Table 6 is read bottom-up.

**Table 6: Growth details** [35].

<table>
<thead>
<tr>
<th>Structure</th>
<th>Thickness</th>
<th>Temperature</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth Stop</td>
<td></td>
<td>150</td>
<td>3:23:12.0</td>
</tr>
<tr>
<td>GaAs:Be N$_a$=1.3*10$^{19}$ cm$^{-3}$</td>
<td>10nm</td>
<td>608</td>
<td>0:08:04.0</td>
</tr>
<tr>
<td>Al$<em>{0.85}$Ga$</em>{0.15}$As:Be N$_a$=2.0*10$^{18}$ cm$^{-3}$</td>
<td>30nm</td>
<td>608</td>
<td>0:03:37.0</td>
</tr>
<tr>
<td>Pause</td>
<td></td>
<td>608</td>
<td>0:01:00.0</td>
</tr>
<tr>
<td>Pause $T_{Ga6}$=920→810 &amp; $T_M$=580→610</td>
<td>580.5→608</td>
<td></td>
<td>0:11:00.0</td>
</tr>
<tr>
<td>GaAs:Be N$_a$=1*10$^{18}$ cm$^{-3}$</td>
<td>150nm</td>
<td>580.5</td>
<td>0:12:37.0</td>
</tr>
<tr>
<td>Pause $T$=540→580</td>
<td></td>
<td>580.5</td>
<td>0:01:00.0</td>
</tr>
<tr>
<td>GaAs</td>
<td>1490nm</td>
<td>580.5</td>
<td>2:05:18.0</td>
</tr>
<tr>
<td>Pause $T_{Ga6}$=903.1→920 &amp; $T_M$=610→580</td>
<td>608→580.5</td>
<td></td>
<td>0:08:30.0</td>
</tr>
<tr>
<td>GaAs:Si N$_d$=5.7*10$^{16}$ cm$^{-3}$</td>
<td>10nm</td>
<td>608</td>
<td>0:01:11.0</td>
</tr>
<tr>
<td>Al$<em>{0.3}$Ga$</em>{0.7}$As:Si N$_d$=4*10$^{18}$ cm$^{-3}$</td>
<td>20nm</td>
<td>608</td>
<td>0:01:40.0</td>
</tr>
<tr>
<td>Pause</td>
<td></td>
<td>608</td>
<td>0:01:00.0</td>
</tr>
<tr>
<td>Pause $T_{Ga6}$=920→903.1 &amp; $T_M$=580→610</td>
<td>580.5→608</td>
<td></td>
<td>0:02:00.0</td>
</tr>
<tr>
<td>GaAs:Si N$_d$=4.0*10$^{18}$ cm$^{-3}$</td>
<td>250nm</td>
<td>580.5</td>
<td>0:25:14.0</td>
</tr>
<tr>
<td>GaAs (311)A: N+</td>
<td></td>
<td>580.5</td>
<td>0:01:01.0</td>
</tr>
</tbody>
</table>

Average growth rate is ~ 2 Å/s. After growth stops, cells cool down and the wafer can be transferred out of the chamber and the machine can be reset. Sections from the wafer are then cleaved (as shown in Figure 18) to check for material growth defects by various material characterization tools discussed next.
Figure 17: Growth layers and solar cell device structure.

Figure 18: Wafer sections cleaved for material characterization.
4.2.3 Material characterization

Material characterization consists of parallel methods that are used to check for defects in the material grown. The four methods used include photoluminescence (PL), atomic force microscopy (AFM), x-ray diffraction (XRD), and transmission electron microscopy (TEM). Each of these methods is described briefly below.

4.2.3.1 Photoluminescence

This is a method used to detect energy levels by optical excitation of the material. This is important since the quantum wires are used to engineer band gaps for broad spectrum absorption and photoluminescence enables the scientist to observe these band gaps. A laser and supporting instruments are used for this purpose.

4.2.3.2 Atomic force microscopy

For this quantum wire project, AFM is used to verify quantum wire structure. This is actually performed on a separate sample where the quantum wires are exposed instead of being sandwiched between different layers of the solar cell structure. This is done only on pre-solar cell growth samples to assess whether the quantum wires grown are of desirable length. The quantum wires are grown on the substrate with a buffer layer in between. This growth is also done using the MBE. However, this is not done for every sample grown. This growth and characterization is done once for every six samples grown.

4.2.3.3 X-ray diffraction

XRD is used to verify the composition and thickness of each layer.

4.2.3.4 Transmission electron microscopy

The TEM is used to ensure there are no strain related defects. The sample must undergo an extensive preparation process before being observed under the TEM. This process uses a
polisher, ion mill, disc saw, hot plate, and optical microscope. This is done because a TEM requires very thin samples since the electron beam must go through the sample to yield an image.

4.2.4 Fabrication

This is the part of the process where the device structure is defined and metal is deposited to form contact pads for wire bonding. The device structure was shown in Figure 15. Fabrication involves the following general procedure:

A. Patterning the 5 mm x 5 mm sample of solar cell material using ultraviolet exposure through a mask onto spin-coated photoresist.

B. Developing the pattern and etching away excess material that will not be part of the active region of the sample.

C. Evaporating metal onto the back side of the sample using an e-beam evaporator and annealing the sample to ensure an ohmic contact is established.

D. Patterning and forming contacts on the front side of the sample using photolithography as described in A and B except with a new mask containing solar cell finger and bus bar patterns.

E. Evaporating metal onto the front side on the photoresist contact pattern and lifting off the sacrificial layers of photoresist.

At this point the device is complete. For testing electrical characteristics, wires need to be bonded onto the sample in a process called electronic packaging.

4.2.5 Electronic Packaging

For wire bonding, a conductive paste is applied onto the sample contact pads and gold wires are bonded using a wire bonder.
4.2.6 Device Characterization

This part of the system tests the device for its efficiency and simulates ambient conditions expected under insolation. The different tests that determine the device’s performance are listed below:

4.2.6.1 I-V C-V measurements

This is the step where current-voltage characteristics and capacitance-voltage characteristics are obtained to derive performance characteristics such as fill factor, maximum output power, etc. I-V characteristics are obtained in the dark as well as with a solar simulator to get a complete I-V curve.

4.2.6.2 Solar simulation

This is an instrument that provides illumination like that of sunlight in order to test the device’s surface reflectance, photon absorption, spectral response, etc.

4.2.6.3 External Quantum Efficiency measurements

External quantum efficiency (EQE) is the ratio of electrons collected to the number of photons incident on the solar cell surface.

4.2.6.4 Deep Level Transient Spectroscopy measurement

Deep level transient spectroscopy (DLTS) is a way to detect recombination centers (or charge carrier traps). These are defects in the material that can keep an electron from contributing to useful current.

4.2.6.5 Hall-effect measurement

The Hall phenomenon is where a voltage is set up across the width of a flat conductor when mutually perpendicular magnetic field and current flow are present. The hall-effect creates
an electric field in a direction perpendicular to both the current direction and magnetic field. This phenomenon is used in solar cells to determine mobility of charge carriers.
CHAPTER 5: IMPLEMENTATION OF LCA PROJECTION ON TEST-BED

Introduction:

This case study assessed the impact of the test-bed system on a key factor - the total energy demand - making the study more than just an inventory analysis. Also, presented LCA analysis is specific to the research phase of the life cycle of QWR-based GaAs PV technology. This is reiterated in the assumptions and limitations section under goal and scope of the study. Some generalizations may apply, for example, to cases that use similar processing techniques, such as other III-V materials. But for the most part this assessment is a subset of a larger LCA on emerging PV technologies. Hence, it is termed as an LCA projection. The results of this case study may be built upon for further analysis. More details are provided in the future work section.

5.1 GOAL AND SCOPE DEFINITION

The goal is stated in Table 7 and scope in Table 8. Assumptions and limitations of this life cycle assessment projection are also provided below.

5.1.1 Goal defined

<table>
<thead>
<tr>
<th>Table 7: Goals of the LCA.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal</td>
</tr>
<tr>
<td>Reason for carrying out the study</td>
</tr>
<tr>
<td>Intended audience</td>
</tr>
<tr>
<td>Comparative assertions for public disclosure</td>
</tr>
</tbody>
</table>
5.1.2 Scope defined

Table 8: Scope of the LCA.

<table>
<thead>
<tr>
<th>Product system under study</th>
<th>Research and development phase of the life cycle of quantum wire based PV cells.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function of the product</td>
<td>To convert sunlight into electricity.</td>
</tr>
<tr>
<td>Functional unit</td>
<td>Efficiency of quantum wire based solar cell.</td>
</tr>
<tr>
<td>Reference flow</td>
<td>One sample of QWR PV cell that is 5mm x 5mm.</td>
</tr>
<tr>
<td>System boundary</td>
<td>Shown in Figure 15.</td>
</tr>
<tr>
<td>Allocation procedures</td>
<td>No co-products.</td>
</tr>
<tr>
<td>Impact assessment methodology and types of impacts</td>
<td>Methodology: numerical summation of energy values. Type of impact: Total energy demand (also the category indicator).</td>
</tr>
<tr>
<td>Value choice</td>
<td>Human effort.</td>
</tr>
<tr>
<td>Critical review</td>
<td>Internal.</td>
</tr>
</tbody>
</table>

As mentioned before, the goal and scope may be refined as the study progresses in order to accommodate challenges in data collection and impact assessment. This may be done multiple times as LCA is an iterative process.

5.1.3 Data quality requirements

Table 9: Data quality requirements.

<table>
<thead>
<tr>
<th>Quality factor</th>
<th>Description [19]</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time-related coverage</strong></td>
<td>age of the data and the minimum length of time over which the data should be collected</td>
<td>Acceptable age of data: within 1 year from the date of the study; minimum length of time: single process flow is sufficient assuming it is representative of most process flows.</td>
</tr>
<tr>
<td><strong>Geographical coverage</strong></td>
<td>geographical area from which data for unit processes should be collected to satisfy the goal of the study</td>
<td>This study covered the R&amp;D process flow of a test bed PV cell system at the University of Arkansas, Fayetteville. This may be representative of similar research institutes in the United States.</td>
</tr>
<tr>
<td>Quality factor</td>
<td>Description [19]</td>
<td>Requirement</td>
</tr>
<tr>
<td>-------------------</td>
<td>------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Technology coverage</td>
<td>specific technology or technology mix</td>
<td>InGaAs QWR intermediate band solar cells grown using molecular beam epitaxy and fabricated using photolithography.</td>
</tr>
<tr>
<td>Completeness</td>
<td>percentage of flow that is measured or estimated</td>
<td>All data was expected to be primary data. Measurements were made using energy meter. If measurement was not possible, best estimates were obtained from manufacturer’s specifications. When data collection was time consuming or characteristically difficult, the data was estimated. At least 80% of flow was directly measured.</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study</td>
<td>Assuming similar equipment and methodology of data collection is used for all unit processes, the results should be easily reproducible. Variation may occur where data has been estimated.</td>
</tr>
<tr>
<td>Sources of the data</td>
<td>the source of data whether primary or secondary</td>
<td>Primary data source: Dr. Gregory Salamo, Institute of Nanoscience and Engineering, University of Arkansas, Fayetteville. Secondary data source: manufacturer’s specifications or technical support representative of certain equipment where primary data could not be obtained.</td>
</tr>
<tr>
<td>Uncertainty of the information</td>
<td>(e.g. data, models, and assumptions)</td>
<td>Assumption: power usages of equipment that could not be measured have been estimated using manufacturer’s specifications, engineers’ estimates, or technical support specialists’ expertise. Duration of usage of certain equipment may vary since different operator may operate equipment at a different pace.</td>
</tr>
</tbody>
</table>

5.1.4 Assumptions

- All process steps performed by the operators were as described in the process flow in Section 4.2.
- All computers consumed the same amount of power as mentioned in literature [36].
- Equipment idle time was taken as the average time period between consecutive usages.
Energy consumption for heating, ventilation, and air conditioning (HVAC) of the MBE lab was taken as the standard. HVAC energy consumption for all other labs was calculated by considering volume fraction of the lab with respect to the MBE lab. Detailed calculations are provided in Section 5.2.1.4.

All equipment was assumed to be ready for operation.

Liquid nitrogen usage was assumed as material cost and would be useful in a material analysis but is not required for quantifying total energy demand in this study.

- Energy used to produce liquid nitrogen is an upstream (prior to input gate of the study) cost that is outside the scope of this study since it is outside the system boundary.

The study accounted for manpower using body mass ratio and physical activity level as per literature [37].

- For body mass, average mass of a person was assumed to be 70kg.
- For physical activity level, a lightly active lifestyle was assumed.

Calculation details are provided in Section 5.2.1.6.

### 5.1.5 Limitations

Disclaimer: This completed study is not a complete LCA. It is an LCA projection of energy demand on a test bed emerging PV technology research process, and it was conducted on an academic investigation of the growth and fabrication of quantum wires (QWR) on GaAs substrate. It accounted for only the design and development stage (gate to gate) of the life cycle of an emerging PV technology since this technology is yet to be commercialized. The inventory for energy demand generated from this study may be supplemented with further analysis of future stages of development and production of
QWR solar cells once data for production scale system is available. Therefore, this study is a gate-to-gate analysis which allows future LCA analysts to customize process flows for cradle-to-gate and gate-to-grave analysis.

- Energy expended in equipment/facility maintenance was not included since all equipment was assumed to be ready for operation.
- This study did not include material input or output in the data inventory as the focus was only on energy since the impact category of interest is total energy demand. However, the energy consumption inventory of this study will prove beneficial to anyone attempting a complete LCA of the system.
- Noise spectroscopy was excluded as it is rarely used.

This project does not make any comparative assertions and is mainly used for internal knowledge generation. The intention of the project was to quantify energy demand to help develop an energy conscience among technologists working in the energy sector.

5.2 LIFE CYCLE INVENTORY

This section presents the raw data collected on energy consumption for each unit process. The data is organized bottom-up: for each process category, the method of sampling and calculation of energy values is described first, followed by a table summarizing the data discussed. For repetitive calculations, such as overhead energy consumption for ventilation, the data collection method, assumptions, and calculations are discussed only for the first occurrence. Exceptions are presented for subsequent occurrences. A consolidated energy table for the entire inventory is presented at the end of this section. Instruments used for measuring energy consumption included:
- P3 International’s *Kill-a-Watt™* energy meter (Figure 19)
- *tif digital powr probe™* PP1000 (Figure 20), and
- A timer

![Image of P3 International's Kill-a-Watt™ energy meter](image1.png)

**Figure 19:** P3 International *Kill-a-Watt™* Energy Meter connected (a), wall side (b), and equipment side (c).

### 5.2.1 Material Growth

Material growth process is the core of the process flow where the quantum wire solar cell material is grown using a high-precision bottom-up approach. This process involves use of the MBE facility. Instrument used to measure power drawn by MBE instruments was measured using a clamp-on ammeter. A clamp-on ammeter is shown in figure 20.

![Image of clamp-on ammeter](image2.png)
5.2.1.1 Energy consumption for MBE equipment during growth

The MBE machine (Figure 21) is used for material growth.

The MBE machine processed one 2” wafer at a time. For this study, a quarter sector of a 2” diameter wafer was processed. This operation took 5.6 hours: 1.5 hours to warm up the cell (substrate), 3.4 hours to grow material on the substrate, and 45 minutes to cool the wafer down before it could be removed from the machine. The clamp-on ammeter/digital multimeter was...
used to measure power drawn by the MBE machine. This was done while the equipment was being used for growth of a sample. The power was found to be 14.12 kW average over the duration of growth. For the entire duration, energy consumption = 14.12 kW x 5.60 h = 79.1 kWh. Therefore, energy consumption for MBE equipment during growth amounted to 79.1 kWh.

5.2.1.2 Energy consumption for MBE equipment at idle state

The MBE lab is a shared space that is used by other project groups that require high precision molecular beam epitaxial growth. The lab is utilized for at most two growth processes in a day. When the MBE machine is not in use, it is in a standby mode (or idle state). While the machine is idling, it continues to maintain desired temperature and pressure within its chambers. This is almost as energy intensive as the operation mode. The standby energy was measured using the clamp-on ammeter/digital multimeter and the power drawn was found to be 5.68 kW. Since the equipment was generally used for two growth processes in a day, it was in its operational mode for 5.60 h x 2 = 11.2 h. This means, it stayed in its idle state for 24.0 h – 11.2 h = 12.8 h. 12.8 h/2 = 6.40 h of idle MBE time was allocated to this project for a single sample growth. For the entire duration, energy consumption for the idling MBE equipment = 5.68 kW x 6.40 h = 36.4 kWh. Therefore, energy consumption for the idling MBE equipment amounted to 36.4 kWh.

5.2.1.3 Energy consumption for MBE lab illumination

The MBE facility had 25 overhead light fixtures, each with 3 lights per fixture. They were 28 W T-5 lights. The same type of lights were used in most other labs as well. The MBE gowning room had two T-5 tubes. 28W is the standard wattage for all these lights as well. For the MBE facility, the total wattage while all lights were on was calculated as:
\[ \left( \frac{28\ W}{\text{tube}} \times \frac{3\ \text{tubes}}{\text{fixture}} \times 25\ \text{fixtures} \right) + \left( \frac{28\ W}{\text{tube}} \times 2\ \text{tubes} \right) = 2156\ W \quad \text{(Equation 1)} \]

All lights were ON during processing, and only 10 tubes were ON when no one is in the lab (idle time).

Therefore, effective energy consumption due to MBE facility illumination:

\[ (2156\ W \times 5.60\ h) + (28\ W \times 10\ \text{tubes} \times 6.40\ h) = 13862\ \text{Wh} = 13.86\ \text{kWh} \quad \text{(Equation 2)} \]

Therefore, 13.87 kWh of electricity was consumed toward illumination on the MBE lab.

### 5.2.1.4 Heating, Ventilation, and Air Conditioning for MBE

Heating, Ventilation, and Air Conditioning (HVAC) is a critical aspect in the functioning of clean room equipment, and user ease. To maintain a class 1000 clean room such as the MBE lab, HVAC and all air filters must be ON at all times. This is an overhead that must be accounted for in the total energy demand of the process. Data for HVAC energy consumption was provided by the architects that designed the building. It was found that 55,204 Btu/h [38] was used from the central heating plant in order to maintain desirable temperature and humidity in the MBE lab. This summarized quantity was the best information that could be obtained for HVAC for the MBE lab.

\[ \text{Power drawn} = \left( \frac{55204\ \text{Btu}}{\text{h}} \right) \left( \frac{1055.056\ J}{\text{Btu}} \right) \left( \frac{1\ \text{h}}{3600\ \text{s}} \right) = 16179\ W = 16.179\ kW \quad \text{(Equation 3)} \]

Total MBE time allocated for one growth = 5.6 h of growth time + 6.4 h of standby time = 12.0 hours total time. For 12 hours of MBE time allocated to this process flow,

\[ \text{HVAC energy consumption} = 16.179\ kW \times 12\ h = 194.15\ kWh \quad \text{(Equation 4)} \]

HVAC energy consumption is directly proportional to the volume of the facility. This factor was used to estimate the HVAC energy consumption for other labs and offices. The MBE lab’s dimensions were measured as 69 ft x 28 ft x 10 ft, which is a volume of 19,320 ft³. Volume
fraction of other lab spaces with respect to MBE lab volume was used as an estimator for HVAC energy consumption of other labs.

Other factors such as energy expended on fume hoods were also accounted for. For the MBE lab, it was estimated that about half of the power drawn for HVAC was used in the two fume hoods of the lab. One was a standard fume hood, while the other was a walk-in fume hood.

The walk-in fume hood was estimated to consume twice as much energy (for HVAC) as the standard fume hood. Therefore, it was decided that for HVAC energy demand calculation purposes, there are three standard fume hoods in the MBE lab. Half of the power drawn is 8.0895 kW. This means approximately 8.00895 kW is drawn for heating the non-fume hood space in the lab, and another 8.090 kW is drawn for the three equivalent fume-hood spaces. About 2.6965 kW was the power drawn to heat each equivalent fume hood. This value was also used when estimating energy consumption for fume hoods in other labs.

5.2.1.5 HEPA filters for MBE

High Efficiency Particulate Air (HEPA) filters are essential to ensure only clean air is emitted into the environment. There were a total of 36 HEPA filter motors for the nano building. Two of these motors were allocated for the MBE lab. Each motor’s rated power was 1HP and each ran at about 35% rated load. Therefore, power drawn by two HEPA filter motors was:

\[
2 \text{ motors} \times 1 \frac{\text{HP}}{\text{motor}} \times 0.746 \frac{\text{kW}}{\text{HP}} \times 0.35 \text{ load factor} = 0.52 \text{ kW} \quad (\text{Equation 5})
\]

For 12 hours allocated to 1 cycle of MBE usage, energy consumed by HEPA filters in MBE lab = 0.52 kW x 12 h = 6.24 kWh.

5.2.1.6 Human effort

Life Cycle Analyses usually do not include manpower or human effort. This was one of the value additions to this case study. Human effort is the energy requirement of an adult.
Detailed description is provided in reference [39]. Human effort was quantified as follows:

$$\text{TEE} = \text{PAL} \times \text{BMR} \quad (\text{Equation 6})$$

where TEE is the total energy expenditure per unit time (i.e. power) and PAL is the physical activity level expressed in terms of BMR.

$$\text{PAL} = \text{PAR} \quad (\text{Equation 7})$$

where PAR is the physical activity ratio. It is the energy cost per hour of a particular activity relative to energy cost per hour of sleeping. For this case, PAR was assumed to be 1.60 which represents a light activity lifestyle. BMR is the basal metabolic rate expressed in MJ/day and can be calculated as:

$$\text{BMR} = (A \times \text{mass}) + B \quad (\text{Equation 8})$$

where A and B are constants depending on the gender and age of the person. For males between the ages of 18 and 30, A = 0.063 and B = 2.896. For females between the ages of 18 and 30, A = 0.063 and B = 2.036.

Assuming average weight to be 70 kg, male BMR is estimated as $0.063 \times 70 + 2.896 = 7.306$ MJ/day. For 70 kg, female BMR was estimated as $0.062 \times 70 + 2.036 = 6.376$ MJ/day. Average BMR for both male and female was $(7.306 + 6.376)/2 = 6.841$ MJ/day.

$$\left( \frac{6.841 \text{ MJ}}{\text{day}} \right) \left( \frac{1 \text{ day}}{24 \text{ h}} \right) \left( \frac{1000000 \text{ J}}{1 \text{ MJ}} \right) \left( \frac{1 \text{ h}}{3600 \text{s}} \right) = 79.18 \text{ W} \quad (\text{Equation 9})$$

$$\text{TEE} = \text{PAL} \times \text{BMR} = \text{PAR} \times \text{BMR} \quad (\text{Equation 10})$$

$$\text{TEE} = 1.60 \times 79.18 \text{ W} = 127 \text{ W} \quad (\text{Equation 11})$$

Therefore, power of average human effort was calculated to be 127 W. This value was utilized throughout the study to quantify human effort. For supervising material growth in the MBE lab for 5.60 h, the human effort involved was
Energy flow for the Material Growth phase by MBE is tabulated in Table 10 below.

**Table 10: Energy inventory for material growth phase.**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Power Use (kW or kVA) per sample</th>
<th>Time (h) per sample</th>
<th>Energy consumed (kWh) per sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE equipment during growth</td>
<td>14.12</td>
<td>5.60</td>
<td>79.1</td>
</tr>
<tr>
<td>MBE equipment at idle state</td>
<td>5.68</td>
<td>6.40</td>
<td>36.4</td>
</tr>
<tr>
<td>Lighting</td>
<td>-</td>
<td>-</td>
<td>13.9</td>
</tr>
<tr>
<td>HVAC</td>
<td>16.179</td>
<td>11.60</td>
<td>194.15</td>
</tr>
<tr>
<td>HEPA filters</td>
<td>0.52</td>
<td>11.60</td>
<td>6.24</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>5.60</td>
<td>0.711</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>330.5</strong></td>
</tr>
</tbody>
</table>

5.2.2 Modeling and simulation

This step was performed before material growth process. In this step researchers ensured the predicted model works in a simulated environment. Design parameters were finalized based on computer simulations. This is the process category where one hour of operation is required by one person on one computer. Modeling and simulation can be done in an office with minimal overhead.

5.2.2.1 Computer use

Average power drawn by a standard desktop computer while it is ON is 73.97 W, and while it is in SLEEP mode is 21.13 W [36]. These are the standard values that were accepted for power drawn by computers for other processes as well. For one hour of simulations, energy drawn by computer = 73.97 W * 1 h = 73.97 Wh = 0.07397 kWh.
5.2.2.2 Human Effort

Human effort for an hour amounts to \(127 \text{ W} \times 1 \text{ h} = 127 \text{ Wh} = 0.127 \text{ kWh}\) of energy.

This was the standard value calculated in Section 5.2.1.6.

5.2.2.3 Illumination

A standard office space uses four T-5 tube lights. Energy spent on office space illumination = 4 tubes \(*\) 28 W/tube \(*\) 1 h = 112 Wh = 0.112 kWh.

5.2.2.4 HVAC energy consumption

The volume of a standard office space was 11 ft \(*\) 11 ft \(*\) 10 ft = 1210 ft\(^3\). HVAC power drawn for this size of room was calculated using the volume fraction of the room with respect to the MBE lab as:

\[
1210 \text{ ft}^3 \times \left(\frac{8.09 \text{ kW}}{19320 \text{ ft}^3}\right) = 0.507 \text{ kW} \quad \text{(Equation 13)}
\]

0.507 kW \(*\) 1 h = 0.507 kWh of energy is used for HVAC of a standard office over an hour.

Table 11 provides the energy consumption values used for this phase of the process flow.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Power Use (kW or kVA) per sample</th>
<th>Time (h) per sample</th>
<th>Energy consumed (kWh) per sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer use</td>
<td>0.0739</td>
<td>1</td>
<td>0.0739</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>1</td>
<td>0.127</td>
</tr>
<tr>
<td>Lighting</td>
<td>0.112</td>
<td>1</td>
<td>0.112</td>
</tr>
<tr>
<td>HVAC</td>
<td>0.507</td>
<td>1</td>
<td>0.507</td>
</tr>
</tbody>
</table>
5.2.3 Material characterization

This is a set of parallel processes that take place once for every three samples grown. Hence the energy consumption reported is one-third of the measured/calculated energy demand. The parallel processes include TEM analysis, XRD analysis, AFM analysis, and Photoluminescence.

5.2.3.1 Photoluminescence

Instruments required for photoluminescence (PL) include laser, InGaAs CCD detector, and supporting equipment such as chiller, compressor, vacuum pump, and temperature controller. Primary data was collected for all the components listed above except the compressor, which was obtained from a customer care representative of the manufacturing company.

5.2.3.1.1 CCD Detector

The InGaAs CCD detector’s power use was measured using the energy meter as a constant 43.5 W. The CCD detector was always ON. Since photoluminescence equipment was used once a day, 24 hours was taken as the duration of use of the components that are never turned off. Hence, the energy consumption of the CCD Detector was calculated to be $0.0435 \text{ W} \times 24 \text{ h} = 1.044 \text{ kWh}$.

5.2.3.1.2 Chiller

The chiller showed a constant power draw of 97.5 W. Its usage duration was typically five hours. Therefore energy consumption = $0.0975 \text{ kW} \times 5 \text{ h} = 0.4875 \text{ kWh}$.

5.2.3.1.3 Vacuum pump

The vacuum pump registered variable power over time. The breakdown is shown in Table 12 below. Total energy consumption for the vacuum pump was 1.20 kWh.
Table 12: Breakdown for vacuum pump power consumption.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand by</td>
<td>0.0179</td>
<td>20.000</td>
<td>0.358</td>
</tr>
<tr>
<td>Roughing pump</td>
<td>.395</td>
<td>0.083</td>
<td>0.033</td>
</tr>
<tr>
<td>Fine pump</td>
<td>.381</td>
<td>2.000</td>
<td>0.762</td>
</tr>
<tr>
<td>Shutdown</td>
<td>.290</td>
<td>0.167</td>
<td>0.048</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.201</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.3.1.4 Laser

The laser’s power draw was measured while it was in standby mode, while being turned on, and while it was being used at full power. The breakdown is given below in Table 13 along with duration and energy consumption. The total energy consumed for laser was therefore 2.46 kWh + 0.04 kWh + 0.774 kWh = 3.27 kWh.

Table 13: Breakdown for laser power consumption.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand by</td>
<td>0.117</td>
<td>21</td>
<td>2.46</td>
</tr>
<tr>
<td>Power up</td>
<td>0.120</td>
<td>0.33</td>
<td>0.040</td>
</tr>
<tr>
<td>Full power</td>
<td>0.258</td>
<td>3</td>
<td>0.774</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.274</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.3.1.5 Temperature controller

The temperature controller also showed a constant power draw. The power drawn was 13.6 W. Therefore, energy consumed = 0.0136 kW * 5 h = 0.068 kWh.
5.2.3.1.6 Compressor

The compressor’s energy use could not be measured as it was connected to other equipment that could not be disconnected. The customer care representative for the compressor’s manufacturer provided an estimate that 8.5A of current is drawn at steady state. Therefore, 8.5 A * 230 V = 1955 VA. Over five hours, this amounted to 1.955 kVA * 5h = 9.78 kVAh.

5.2.3.1.7 Illumination

Very little illumination was required since photoluminescence is done mostly in the dark. Two T-5 lights provide illumination to the 3200 ft\(^3\) lab. They were estimated to be ON for 2.5 hours while an operator is in the lab. 2 tubes * 28 W/tube = 56 W. Over 2.5 hours, total consumption is 56 W * 2.5 h = 140 Wh.

5.2.3.1.8 Computer

The computer stayed on for 5 hours while each session was in progress. Standby time = 19.5 hours. Energy consumption for computer use = 74 W * 5 h + 21.13 W * 19.5 h = 780 Wh = 0.78 kWh.

5.2.3.1.9 Human effort

An operator worked in the lab for 2.5 hours for each time photoluminescence needed to be done. This translates to a human effort of 0.127 kW * 2.5 h = 0.318 kWh.

5.2.3.1.10 HVAC

The PL lab had a volume of 16 ft * 20 ft * 10 ft = 3200 ft\(^3\). That is 0.1656 times the volume of the MBE lab. Therefore, the energy consumption for HVAC of this lab was calculated as:

\[
\frac{3200 \text{ ft}^3}{19320 \text{ ft}^3} \times 8.09 \text{ kW} = 1.34 \text{ kW}
\]  
\hspace{2cm} \text{(Equation 14)}
1.34 kW * 24 h = 32.16 kWh  
(Equation 15)

where twenty four hours was the standard duration between two PL measurements.

Summarized results for PL energy consumption is shown in Table 14 with a 1/3 factor to incorporate for the fact that material characterization was performed for only one in three samples grown.

Table 14: Energy inventory for PL.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
<th>1/3 Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAs CCD detector</td>
<td>0.0435</td>
<td>24</td>
<td>1.044</td>
<td>0.348</td>
</tr>
<tr>
<td>Chiller</td>
<td>0.0975</td>
<td>5</td>
<td>0.4875</td>
<td>0.1625</td>
</tr>
<tr>
<td>Vacuum pump</td>
<td>-</td>
<td>-</td>
<td>1.201</td>
<td>0.400</td>
</tr>
<tr>
<td>Laser</td>
<td>-</td>
<td>-</td>
<td>3.274</td>
<td>1.091</td>
</tr>
<tr>
<td>Temperature controller</td>
<td>0.0136</td>
<td>5</td>
<td>0.068</td>
<td>0.023</td>
</tr>
<tr>
<td>Compressor</td>
<td>1.955</td>
<td>5</td>
<td>9.78</td>
<td>3.26</td>
</tr>
<tr>
<td>Illumination</td>
<td>0.056</td>
<td>2.5</td>
<td>0.140</td>
<td>0.047</td>
</tr>
<tr>
<td>Computer</td>
<td>-</td>
<td>-</td>
<td>0.78</td>
<td>0.26</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>2.5</td>
<td>0.318</td>
<td>0.106</td>
</tr>
<tr>
<td>HVAC</td>
<td>1.34</td>
<td>24</td>
<td>32.16</td>
<td>10.72</td>
</tr>
</tbody>
</table>

5.2.3.2 TEM Sample Preparation

Before using TEM, the sample needs to be prepared in order that TEM analysis can give best results. This step uses several different equipment such as a hot plate, optical microscope, polisher, ion mill, and disc saw.

5.2.3.2.1 Hot plate
The hot plate consumed 556 W for heating up the plate from room temperature to desired temperature. This took about a minute. To stay at the same temperature it consumed 2.2 W. And to maintain temperature by making small adjustments took 32 W. The system switched between 2.2 W consumption and 32 W consumption over 4 hours. The total energy consumed by the hot plate was therefore

$$\left( 556 \text{ W} \times \frac{1}{60} \text{ h} \right) + (2.2 \text{ W} \times 2 \text{ h}) + (32 \text{ W} \times 2 \text{ h}) = 77.67 \text{ Wh} \quad \text{(Equation 16)}$$

5.2.3.2.2 Microscope

The microscope drew a constant 81 W throughout its 10 minutes use. Thus energy consumed by the microscope was 13.5 Wh.

5.2.3.2.3 Polisher

The polisher consumed 9.6 W for 20 minutes. At a higher speed it consumed 29.1 W for 3.5h. At an even higher speed, consumption increased to 84 W. This lasted about 15 minutes. Overall, the polisher consumed 126 Wh of energy:

$$\left( 9.6 \text{ W} \times 0.33 \text{ h} \right) + (29.1 \text{ W} \times 3.5 \text{ h}) + (84 \text{ W} \times 0.25 \text{ h}) = 126.02 \text{ Wh} \quad \text{(Equation 17)}$$

5.2.3.2.4 Ion mill

The ion mill had variable power consumption. Startup took 2 minutes and it drew 173 W. Chamber preparation took 3 minutes and consumed 351 W. Ion milling is a long process. This instrument took 6.5 hours to mill through the sample and it drew 353 W during the process. When the instrument was in its idle state, it drew 155 W. The instrument is in idle state for about 48 hours, which is the typical time between two measurements. Therefore, the total energy consumption of ion milling one sample was:

$$\left( 173 \text{ W} \times \frac{2}{60} \text{ h} \right) + \left( 351 \text{ W} \times \frac{3}{60} \text{ h} \right) + (353 \text{ W} \times 6.5 \text{ h}) + (155 \text{ W} \times 48 \text{ h}) \quad \text{(Equation 18)}$$
5.2.3.2.5 Disc Saw

The disc saw drew 15 W for the first 15 minutes of operation and 18.9 W for the remaining 10 minutes of operation. Overall, the equipment drew 6.9 Wh, calculated as below:

\[(15 \text{ W} * 0.25 \text{ h}) + \left(18.9 \text{ W} * \frac{10}{60}\right) = 6.9 \text{ Wh}\]  
(Equation 19)

5.2.3.2.6 Illumination

The TEM sample prep room has two luminaires with two tubes in each. Total energy consumption for illumination of the room is:

\[28 \text{ W} * 2 \text{ fixtures} * 2 \frac{\text{tubes}}{\text{fixture}} * 4 \text{ h} = 112 \text{ W} * 4 \text{ h} = 0.448 \text{ kWh}\]  
(Equation 20)

where 9.1 h is the total time for the TEM sample prep where human involvement is required.

5.2.3.2.7 Human effort

Human effort also uses the same calculation as in the previous section:

\[127 \text{ W} * 2.5 \text{ h} = 0.318 \text{ kWh}\]  
(Equation 21)

5.2.3.2.8 HVAC

HVAC consumption depends on the volume of the room. The TEM sample prep room is a 10.5 ft x 10 ft x 10 ft = 1050 ft³. Volume fraction compared to MBE lab is 1050/19320 = 0.0543. HVAC power for this volume is therefore, 8.09 kW * 0.0543 = 0.440 kW. The time allocated to TEM sample prep for this sample is 63.3 h which is the sum of all the equipment operation durations. This includes the average time period between any two sample prep operations. Total energy consumed by HVAC for the TEM sample preparation room:

\[0.440 \text{ kW} * 63.3 \text{ h} = 27.85 \text{ kWh}\]  
(Equation 22)
Therefore, 27.9 kWh of energy was consumed for TEM sample preparation. Summary of the above data collected is provided in Table 15 below. Included is the one-third correction factor for material characterization.

Table 15: Energy inventory for TEM Sample Preparation.

<table>
<thead>
<tr>
<th>Equipment/operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
<th>1/3 Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot plate</td>
<td>-</td>
<td>-</td>
<td>0.078</td>
<td>0.026</td>
</tr>
<tr>
<td>Microscope</td>
<td>0.081</td>
<td>0.17</td>
<td>0.014</td>
<td>0.005</td>
</tr>
<tr>
<td>Polisher</td>
<td>-</td>
<td>-</td>
<td>0.126</td>
<td>0.042</td>
</tr>
<tr>
<td>Ion mill</td>
<td>-</td>
<td>-</td>
<td>9.76</td>
<td>3.25</td>
</tr>
<tr>
<td>Disc saw</td>
<td>-</td>
<td>-</td>
<td>0.0069</td>
<td>0.0023</td>
</tr>
<tr>
<td>Lighting</td>
<td>0.112</td>
<td>4</td>
<td>0.448</td>
<td>0.149</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>2.5</td>
<td>0.318</td>
<td>0.106</td>
</tr>
<tr>
<td>HVAC</td>
<td>0.44</td>
<td>63.3</td>
<td>27.85</td>
<td>9.28</td>
</tr>
</tbody>
</table>

5.2.3.3 TEM

5.2.3.3.1 TEM Analysis

The energy consumption of TEM (FEI Titan 80-300) could not be measured since accessing the power panel would require shutting down the equipment. Shutting down any large electron microscope involves a large down-time and inconvenience to patrons. For this reason, the TEM’s power consumption was acquired from the manufacturer. According to an FEI technical support representative, the TEM draws 10 kW of power when all microscope options are ON. FEI confirmed that all microscope options are ON at all times. This includes the time
when the equipment is ON but not in active use (i.e. idle state) [40]. However, the TEM for this study was not operated at its maximum potential. The 300 keV electron gun was usually operated at 80 keV. This was accounted for by taking a factor of the full capacity 10 kW power consumption.

\[
\text{Adjusted Power Consumption} = \left( \frac{80}{300} \right) \times 10 \text{ kW} = 2.7 \text{ kW} \quad \text{(Equation 23)}
\]

The average time period of the TEM usage is calculated as below:

During school semester (4 months): 8 to 24 hours (average = 16 h)

During summer/winter months (2 months): 1 week = 168 h.

During school semester (4 months): 
\[
4 \text{ months} \times \frac{30 \text{ days}}{1 \text{ month}} \times \frac{24 \text{ hours}}{1 \text{ day}} \times \frac{1 \text{ usage}}{16 \text{ hours}} = 180 \text{ usages} \quad \text{(Equation 24)}
\]

During summer/winter months (2 months): 
\[
2 \text{ months} \times \frac{4 \text{ weeks}}{1 \text{ month}} \times \frac{1 \text{ usage}}{1 \text{ week}} = 8 \text{ usages} \quad \text{(Equation 25)}
\]

This translated to 188 usages of the equipment over a six month period. That amounts to an average usage time period of:

\[
\frac{6 \text{ months}}{188 \text{ usages}} \times \frac{30 \text{ days}}{1 \text{ month}} \times \frac{24 \text{ hours}}{1 \text{ day}} = 23 \text{ hours/usage} \quad \text{(Equation 26)}
\]

Therefore, energy consumed for each sample analyzed = 2.7 kW * 23 h = 62.1 kWh.

5.2.3.3.2 Computer

The computers were operated for three hours, and they were idle for ~23 hours. The calculated energy consumption for computers for TEM analysis was:

\[
2 \times (74 \text{ W} \times 3 \text{ h} + 21.13 \text{ W} \times 23 \text{ h}) = 1415 \text{ Wh} = 1.415 \text{ kWh} \quad \text{(Equation 27)}
\]

5.2.3.3.3 Human effort

Human effort for three hours amounted to:

\[
0.127 \text{ kW} \times 3 \text{ hours} = 0.381 \text{ kWh} \quad \text{(Equation 28)}
\]
5.2.3.3.4 Illumination

The TEM room does not use the standard tube lights; it uses 4 small pot lights (10W each). Most of the TEM operation is done in the dark. It is assumed that lights are on for only one hour of the operation. Therefore, energy consumption for the lighting of the room:

\[ 40 \text{ W} \times 1 \text{ h} = 40 \text{ Wh} = 0.04 \text{ kWh} \]  \hspace{1cm} (Equation 29)

5.2.3.3.5 HVAC

The volume of the TEM room is 11 x 11 x 10 cu.ft. = 1210 ft\(^3\). Volume fraction with respect to the MBE lab = 1210/19320 = 0.0626. HVAC power consumption for this volume:

\[ 8.09 \text{ kW} \times 0.0626 = 0.506 \text{ kW} \]  \hspace{1cm} (Equation 30)

The average time period allocated to the use of TEM was 23 hours. Therefore, energy consumed to maintain HVAC of the TEM lab space was:

\[ 506 \text{ W} \times 23 \text{ h} = 11.6 \text{ kWh} \]  \hspace{1cm} (Equation 31)

Table 16 summarizes the energy consumption for TEM analysis:

**Table 16: Energy inventory for TEM Analysis.**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
<th>1/3 Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEM analysis</td>
<td>2.7</td>
<td>23</td>
<td>62.1</td>
<td>21</td>
</tr>
<tr>
<td>Computer use</td>
<td>-</td>
<td>-</td>
<td>1.415</td>
<td>0.472</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>3</td>
<td>0.381</td>
<td>0.127</td>
</tr>
<tr>
<td>Lighting</td>
<td>0.04</td>
<td>1</td>
<td>0.04</td>
<td>0.013</td>
</tr>
<tr>
<td>HVAC</td>
<td>0.506</td>
<td>23</td>
<td>11.6</td>
<td>3.88</td>
</tr>
</tbody>
</table>
5.2.3.4 XRD

5.2.3.4.1 XRD analysis

The Philips X-ray diffractometer system is usually operated at 1.6 kW. Power consumption was not measured because its electrical panel was inaccessible. Average power consumption was then estimated based on samples analyzed using XRD. The copper radiation is typically delivered at 40 mA and 40 kV [41]:

\[ 40 \text{ mA} \times 40 \text{ kV} = 1600 \text{W} = 1.6 \text{ kW} \]  
(Equation 32)

This is one of the most power consuming parts of the equipment. The equipment is operated for about an hour. Energy consumption during this time = 1.6 kW * 1 h = 1.6 kWh.

5.2.3.4.2 Human effort

Human effort for an hour took up to 127 W * 1 h = 127 Wh.

5.2.3.4.3 HVAC

HVAC power consumption depends on the size of the XRD lab. In this case, the size was a 7 x 12 x 10 cu.ft. = 840 ft³. Volume fraction with respect to the MBE lab = 840/19320 = 0.043.

Power drawn by XRD room HVAC =

\[ 0.043 \times 8.09 \text{ kW} = 0.35 \text{ kW} \]  
(Equation 33)

Energy consumed =

\[ 0.35 \text{ kW} \times 4 \text{ days} \times 24 \text{ h/d} = 33.6 \text{ kWh} \]  
(Equation 34)

5.2.3.4.4 Illumination

The XRD lab had six light fixtures with three tubes in each. 6 fixtures * 3 tubes/fixture * 28 W tube = 504 W. Over the duration of a single XRD run of 1.25 hours, energy consumption due to lighting was 504 W * 1.25 h = 630 Wh.

XRD data is summarized in Table 17.
Table 17: Energy inventory for XRD Analysis.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
<th>1/3 Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XRD analysis</td>
<td>1.60</td>
<td>1</td>
<td>1.60</td>
<td>0.53</td>
</tr>
<tr>
<td>Human Effort</td>
<td>0.127</td>
<td>1</td>
<td>0.127</td>
<td>0.042</td>
</tr>
<tr>
<td>HVAC</td>
<td>0.35</td>
<td>96</td>
<td>33.6</td>
<td>11.2</td>
</tr>
<tr>
<td>Lighting</td>
<td>0.504</td>
<td>1.25</td>
<td>0.63</td>
<td>0.31</td>
</tr>
</tbody>
</table>

5.2.3.5 AFM

5.2.3.5.1 AFM analysis

Power drawn by AFM was measured using the kill-a-watt meter from the time of start-up to shut-down of the system. The system included two computers. Over duration of 35 minutes, the average power draw was found to be 398.5 W. The energy consumption therefore was:

\[ 0.3985 \text{ kW} \times \left( \frac{35}{60} \right) \text{ h} = 0.231 \text{ kWh} \quad \text{(Equation 35)} \]

5.2.3.5.2 Human effort

Human effort included the time to operate the equipment as well as the time to setup. Setup takes an additional 17 minutes. Total operator time was estimated to be 0.875 hours. Therefore, human effort:

\[ 0.127 \text{ kW} \times 0.875 \text{ h} = 0.111 \text{ kWh} \quad \text{(Equation 36)} \]

5.2.3.5.3 HVAC

The volume of the room was 14 ft x 11 ft x 10 ft = 1540 ft³. Volume fraction with respect to the MBE lab = 1540/19320 = 0.0797. Total energy to heat and cool the space =

\[ 0.0797 \times 8.09 \text{ kW} = 0.640 \text{ kW} \quad \text{(Equation 37)} \]
5.2.3.5.4 Illumination

The AFM room had 4 light fixtures with 3 tubes in each. Total energy for lighting AFM lab =

\[ 4 \text{ fixtures} \times 3 \text{ tubes/fixture} \times 0.028 \text{ kW} \times 1.5 \text{ h} = 0.504 \text{ kWh} \quad \text{(Equation 39)} \]

5.2.3.5.5 MBE component of AFM analysis

AFM analysis was done once for every 6 samples grown unlike other material characterization methods that were done once for every 3 samples grown. This can be accounted for by assuming half duty cycle for AFM in addition to the 1/3 duty cycle already established for other material characterization methods. This modification can be seen in Table 18.

AFM is done on pre-solar cell growth sample. This is a special sample grown exclusively for the purpose of AFM analysis. This sample consists of the quantum-wires on the substrate with buffer layer in between. Since a special sample is grown for this purpose, the energy to grow this pre-solar cell sample needs to be accounted for. This energy is almost same as the energy to grow a regular sample since maximum time goes into growing the wires and the buffer layer. Therefore, energy contributed by the other layers is not significant in comparison.

MBE contribution is 330.5 kWh for one sample growth (total calculated from Table 10). This is incorporated in the contribution of AFM analysis. See Table 18.

AFM energy consumption data is summarized in Table 18 below:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
<th>1/2 Energy (kWh)</th>
<th>1/3 Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFM analysis</td>
<td>0.3985</td>
<td>0.58</td>
<td>0.2311</td>
<td>0.1156</td>
<td>0.0385</td>
</tr>
<tr>
<td>Human Effort</td>
<td>0.127</td>
<td>0.875</td>
<td>0.111</td>
<td>0.0555</td>
<td>0.0185</td>
</tr>
</tbody>
</table>

Table 18: Energy inventory for AFM analysis.
Table 19 below summarizes the energy inventory of the material characterization phase.

**Table 19: Energy inventory for material characterization phase.**

<table>
<thead>
<tr>
<th>Process</th>
<th>Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
<th>1/2 Energy (kWh)</th>
<th>1/3 Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL</td>
<td>InGaAs CCD detector</td>
<td>0.0435</td>
<td>24</td>
<td>1.044</td>
<td>0.348</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>Chiller</td>
<td>0.0975</td>
<td>5</td>
<td>0.4875</td>
<td>0.1625</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>Vacuum pump</td>
<td>-</td>
<td>-</td>
<td>1.201</td>
<td>0.400</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>Laser</td>
<td>-</td>
<td>-</td>
<td>3.274</td>
<td>1.091</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>Temperature controller</td>
<td>0.0136</td>
<td>5</td>
<td>0.068</td>
<td>0.023</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>Compressor</td>
<td>1.955</td>
<td>5</td>
<td>9.78</td>
<td>3.26</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>Illumination</td>
<td>0.056</td>
<td>2.5</td>
<td>0.140</td>
<td>0.047</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>Computer</td>
<td>-</td>
<td>-</td>
<td>0.78</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>Human effort</td>
<td>0.127</td>
<td>2.5</td>
<td>0.318</td>
<td>0.106</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>HVAC</td>
<td>1.34</td>
<td>24</td>
<td>32.16</td>
<td>10.72</td>
<td></td>
</tr>
<tr>
<td>TEM Sample Prep</td>
<td>Hot plate</td>
<td>-</td>
<td>-</td>
<td>0.078</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>TEM Sample Prep</td>
<td>Microscope</td>
<td>0.081</td>
<td>0.167</td>
<td>0.014</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>TEM Sample Prep</td>
<td>Polisher</td>
<td>-</td>
<td>-</td>
<td>0.126</td>
<td>0.042</td>
<td></td>
</tr>
<tr>
<td>Process</td>
<td>Operation</td>
<td>Power draw (kW)</td>
<td>Duration (h)</td>
<td>Energy (kWh)</td>
<td>1/3 Energy (kWh)</td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-----------------------</td>
<td>-----------------</td>
<td>--------------</td>
<td>--------------</td>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td>TEM Sample Prep</td>
<td>Ion mill</td>
<td>-</td>
<td>-</td>
<td>9.76</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
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<td>Disc saw</td>
<td>-</td>
<td>-</td>
<td>0.0069</td>
<td>0.0023</td>
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</tr>
<tr>
<td>TEM Sample Prep</td>
<td>Lighting</td>
<td>0.112</td>
<td>4</td>
<td>0.448</td>
<td>0.149</td>
<td></td>
</tr>
<tr>
<td>TEM Sample Prep</td>
<td>Human effort</td>
<td>0.127</td>
<td>2.5</td>
<td>0.318</td>
<td>0.106</td>
<td></td>
</tr>
<tr>
<td>TEM Sample Prep</td>
<td>HVAC</td>
<td>0.440</td>
<td>63.3</td>
<td>27.85</td>
<td>9.28</td>
<td></td>
</tr>
<tr>
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<td>23</td>
<td>62.1</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td>TEM</td>
<td>Computer use</td>
<td>-</td>
<td>-</td>
<td>1.415</td>
<td>0.472</td>
<td></td>
</tr>
<tr>
<td>TEM</td>
<td>Human effort</td>
<td>0.127</td>
<td>3</td>
<td>0.381</td>
<td>0.127</td>
<td></td>
</tr>
<tr>
<td>TEM</td>
<td>Lighting</td>
<td>0.04</td>
<td>1</td>
<td>0.04</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>TEM</td>
<td>HVAC</td>
<td>0.51</td>
<td>23</td>
<td>11.6</td>
<td>3.88</td>
<td></td>
</tr>
<tr>
<td>XRD</td>
<td>XRD analysis</td>
<td>1.60</td>
<td>1</td>
<td>1.60</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>XRD</td>
<td>Human Effort</td>
<td>0.127</td>
<td>1</td>
<td>0.127</td>
<td>0.042</td>
<td></td>
</tr>
<tr>
<td>XRD</td>
<td>HVAC</td>
<td>0.35</td>
<td>96</td>
<td>33.6</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td>XRD</td>
<td>Lighting</td>
<td>0.504</td>
<td>1.25</td>
<td>0.63</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>AFM</td>
<td>AFM analysis</td>
<td>-</td>
<td>-</td>
<td>0.1156</td>
<td>0.0385</td>
<td></td>
</tr>
<tr>
<td>AFM</td>
<td>Human Effort</td>
<td>-</td>
<td>-</td>
<td>0.0555</td>
<td>0.0185</td>
<td></td>
</tr>
<tr>
<td>AFM</td>
<td>HVAC</td>
<td>-</td>
<td>-</td>
<td>30.72</td>
<td>10.24</td>
<td></td>
</tr>
<tr>
<td>AFM</td>
<td>Lighting</td>
<td>-</td>
<td>-</td>
<td>0.252</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>Sample growth for AFM</td>
<td>Sample growth for AFM</td>
<td>-</td>
<td>-</td>
<td>165.3</td>
<td>55.1</td>
<td></td>
</tr>
</tbody>
</table>
5.2.4 Fabrication

This is a set of serial processes where photolithography is performed first, followed by metallization, then annealing, finally photolithography again. Each of the processes makes use of multiple equipment in a specific sequence.

5.2.4.1 Photolithography

This step uses ultraviolet light exposure on photoresist through a mask to form a pattern on the substrate material. The instruments used to perform photolithography are:

- Oven
- Spin coater
- Hot plate
- Mask aligner
- Microscope

Power drawn for the oven, spin coater, hot plate, and microscope was measured using the kill-a-watt meter. Power consumption of the mask aligner could not be measured as it was connected to equipment that could not be shut down. Power consumption and energy calculation for each equipment is provided below.

5.2.4.1.1 Oven

The oven’s power consumption varied between 848 W and 853 W. Average wattage was thus taken to be 851 W. The duration of operation was 24 minutes (including both front and back side processing of sample). Energy consumed = 0.851 kW * 0.40 h = 0.340 kWh.

5.2.4.1.2 Spin coater

When the spin coater was switched from OFF state to ON state, it showed 24.1 W of power being drawn. After a 10 s delay, as the instrument accelerated to 5000 rpm very rapidly,
power consumption went up to 72.2 W. It stayed at 5000 rpm for 30 seconds (0.0083 h) and then decelerated to rest (24.1 W) very rapidly. Total operation time was 4 minutes. Therefore, energy consumed by the spin coater:

\[
(24.1 \text{ W} \times \left(\frac{3.5}{60}\right) \text{ h}) + (72.2 \text{ W} \times \left(\frac{0.5}{60}\right) \text{ h}) = 0.507 \text{ kW}
\]  
(Equation 40)

Since the spin coater is used for processing the front as well as the back side of the sample, its energy contribution was doubled. Therefore, 2.01 Wh * 2 = 4.02 Wh.

5.2.4.1.3 Hot plate

The hot plate’s consumption varied between 14.6 W and 40.3 W. The average was taken to be 27.45 W. The hot plate was operated twice for 3 minutes each. Energy consumed was therefore:

\[
27.45 \text{ W} \times \left(\frac{6}{60}\right) \text{ h} = 2.75 \text{ Wh}
\]  
(Equation 41)

5.2.4.1.4 Mask aligner

The mask aligner lamp dominated power consumption with 194 W. The monitor power consumption (28 W) was found from the equipment specifications as the average power use. The aligner usage time was estimated from prior experience to be approximately 1 minute for exposure without alignment and 6 minutes for exposure with alignment. And the lamp exposure time usually varies between 10s and 20s. Average of 15s was assumed for calculation.

\[
\text{Total energy} = \left(194 \text{ W} \times \frac{15}{3600} \text{ h}\right) + \left(28 \text{ W} \times \frac{7}{60} \text{ h}\right) = 4.075 \text{ Wh}
\]  
(Equation 42)

5.2.4.1.5 Microscope

The microscope power consumption was dominated by the lamp intensity which was set to 106W. The microscope is usually used for 3 minutes. Energy consumption was therefore:
5.2.4.1.6 Illumination

The nanofabrication lab, where photolithography is conducted, had 10 “yellow” lamps, 28 W each, that remained ON for 3 hours (duration of a typical photolithography process). Total energy consumed in illumination = 28 W * 10 lamps * 3 h = 840 Wh.

5.2.4.1.7 HVAC

Volume of the nanofabrication lab was:

\[37 \text{ ft} \times 16 \text{ ft} \times 10 \text{ ft (top floor)} + 13 \text{ ft} \times 13 \text{ ft} \times 10 \text{ ft (gowning area)} + 7 \text{ ft} \times 13 \text{ ft} \times 20 \text{ ft (stairs)}\]  
\[= 5920 \text{ cu.ft.} + 1690 \text{ cu.ft.} + 1820 \text{ cu.ft.} = 9430 \text{ cu.ft}\]  

(Equation 44)

Since half of the lab space was used for photolithography and the other half for metallization, volume allocated to the photolithography process = 9540/2 = 4715 cu.ft. Volume fraction with respect to the MBE lab = 4715/19320 = 0.24. Therefore, HVAC power draw = 0.24 * 8.09 kW = 1.94 kW. Adding to this half of the fume hood contribution, 2.6965kW/2 = 1.35 kW (explained in Section 5.2.1.4), we get 1.94 kW + 1.35 kW = 3.29 kW. Over 24 hours:

\[3.29 \text{ kW} \times 24h = 78.96 \text{ kWh}\]  

(Equation 45)

5.2.4.1.8 HEPA filters

The fume hood in the nanofabrication lab has HEPA filters just as the ones allocated to the MBE lab. Using volume fraction to determine equivalent power drawn by HEPA filters, (4715/19320) * 0.52 kW = 0.13 kW. Half of that is allocated to the metallization part of the lab since the fume hood is shared by both processes (photolithography and metallization). Therefore, HEPA filter contribution from fume hood allocated to the photolithography process = 0.13kW/2 = 0.065 kW. Over 24 hours, that is:

\[106 \text{ W} \times \left(\frac{3}{60}\right)h = 0.005 \text{ kWh}\]  

(Equation 43)
0.065 kW * 24 h = 1.56 kWh  
(Equation 46)

5.2.4.1.9 Human effort

Human effort of two hours was involved in the photolithography process. Therefore, total effort = 127 W * 2 h = 254 Wh.

Table 20 summarizes the above information:

Table 20: Energy inventory for photolithography.

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven</td>
<td>0.851</td>
<td>0.40</td>
<td>0.340</td>
</tr>
<tr>
<td>Spin Coater</td>
<td>-</td>
<td>-</td>
<td>0.004</td>
</tr>
<tr>
<td>Hot Plate</td>
<td>0.027</td>
<td>0.1</td>
<td>0.0027</td>
</tr>
<tr>
<td>Mask Aligner</td>
<td>-</td>
<td>-</td>
<td>0.004</td>
</tr>
<tr>
<td>Microscope</td>
<td>0.11</td>
<td>0.05</td>
<td>0.0055</td>
</tr>
<tr>
<td>Lighting</td>
<td>0.28</td>
<td>3</td>
<td>0.84</td>
</tr>
<tr>
<td>HVAC</td>
<td>3.29</td>
<td>24</td>
<td>78.96</td>
</tr>
<tr>
<td>HEPA filters</td>
<td>0.065</td>
<td>24</td>
<td>1.56</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>2</td>
<td>0.254</td>
</tr>
</tbody>
</table>

5.2.4.2 Metallization

This was the part of device fabrication where metal contact is made. Equipment used for metallization included:

- E-beam evaporator
- Power supply for the evaporator
- Turbo pumps for the evaporator
- Chiller for the evaporator
Ultrasonic bath

Energy consumption for each equipment is explained below:

5.2.4.2.1 E-beam evaporator

The e-beam evaporator had a three phase power supply. Due to difficulty in measuring the line current, an estimate was obtained from the manufacturer. Maximum power used to energize the electron gun is 3kW. However, this much power is not usually used since the current drawn by the electron gun depends on the melting point of the metal being melted and the rate of evaporation. Most metals require less than 80mA with the exception of platinum. Actual current used for evaporation was recorded in a usage log. Table 21 below is a snapshot of the usage log.

**Table 21: E-beam evaporator usage log.**

<table>
<thead>
<tr>
<th>Side of sample</th>
<th>Material</th>
<th>Thickness (nm)</th>
<th>Current (mA)</th>
<th>Rate (nm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom side</td>
<td>AuGe</td>
<td>75</td>
<td>83</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Ni</td>
<td>15</td>
<td>140</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Au</td>
<td>200</td>
<td>77</td>
<td>0.47</td>
</tr>
<tr>
<td>Top side</td>
<td>AuZn</td>
<td>100</td>
<td>112</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>Au</td>
<td>200</td>
<td>75</td>
<td>0.41</td>
</tr>
</tbody>
</table>

The electron gun voltage was set at 3kV. Using Table 21, following calculations were performed for the energy consumption of metal evaporation on each side of the sample. 30s was taken as the average time of evaporation during which the shutter of the equipment was still closed.

For the bottom side:
Energy for evaporating AuGe =

\[3 \text{kV} \times 83 \text{ mA} \times \left( \frac{75 \text{ nm}}{0.33 \text{ nm/s}} + 30 \text{ s} \right) \times \frac{1 \text{ h}}{3600 \text{ s}} = 17.8 \text{ Wh}\]  
(Equation 47)

Energy for evaporating Ni =

\[3 \text{kV} \times 140 \text{ mA} \times \left( \frac{15 \text{ nm}}{0.22 \text{ nm/s}} + 30 \text{ s} \right) \times \frac{1 \text{ h}}{3600 \text{ s}} = 11.5 \text{ Wh}\]  
(Equation 48)

Energy for evaporating Au =

\[3 \text{kV} \times 77 \text{ mA} \times \left( \frac{200 \text{ nm}}{0.47 \text{ nm/s}} + 30 \text{ s} \right) \times \frac{1 \text{ h}}{3600 \text{ s}} = 29.2 \text{ Wh}\]  
(Equation 49)

Total = 17.8 Wh + 11.5 Wh + 29.2 Wh = 58.5 Wh = 0.0585 kWh

For the top side:

Energy for evaporating AuZn =

\[3 \text{kV} \times 112 \text{ mA} \times \left( \frac{100 \text{ nm}}{0.43 \text{ nm/s}} + 30 \text{ s} \right) \times \frac{1 \text{ h}}{3600 \text{ s}} = 24.5 \text{ Wh}\]  
(Equation 50)

Energy for evaporating Au =

\[3 \text{kV} \times 75 \text{ mA} \times \left( \frac{200 \text{ nm}}{0.41 \text{ nm/s}} + 30 \text{ s} \right) \times \frac{1 \text{ h}}{3600 \text{ s}} = 32.4 \text{ Wh}\]  
(Equation 51)

Total = 24.5 Wh + 32.4 Wh = 56.9 Wh = 0.0569 kWh.

Total energy for evaporation was therefore:

\[0.0585 \text{ kWh} + 0.0569 \text{ kWh} = 0.1154 \text{ kWh}\]  
(Equation 52)

0.1154 kWh was used for the by the e-beam evaporator for metallizing contacts on the top and bottom of the sample. This did not include start up, pump down, and vent processes, which are discussed next.
5.2.4.2.2 Evaporator power supply

The power supply for the e-beam evaporator was rated at 208 V, 6 kVA. But according to technical support representative for the equipment, it draws only 600mA (max) at all times. Sensible power draw is therefore, $208 \times 0.6 = 124.8$ W. Over the 24 hours that was allocated to e-beam evaporator use for this sample, the energy consumption was $124.8 \times 24 = 2995.2$ Wh $\sim 3$ kWh.

5.2.4.2.3 Turbo pumps

The turbo pumps for the evaporator are always on. They consume 1.74 kW while they are ON. Over 24 hours, that is $1.74 \times 24 = 41.52$ kWh.

5.2.4.2.4 Chillers

The chillers are also always ON and draw 4.5 kW. Over 24 hours, that is an energy consumption of $4.5 \times 24 = 108$ kWh.

5.2.4.2.5 Ultrasonic bath

The ultrasonic bath power draw was measured using the kill-a-watt meter. It measured variable power draw that ranged between 70.7 and 74.9 W of power draw. Average = 72.8 W. The ultrasonic bath was used for about an hour. Energy consumed was therefore, $72.8 \times 1 = 72.8$ Wh.

5.2.4.2.6 Illumination

Illumination for the metallization section of the nano-fabrication lab was provided by 11 yellow and orange UV blocking lights. Each tube consumed the standard 28 W. Over 3 hours of operation and no-occupancy delay, total energy consumption due to lighting amounted to $28 \times 11 \times 3 = 924$ Wh.
5.2.4.2.7 HVAC

Looking at Section 5.2.4.1 on photolithography, the energy consumption for HVAC is same as the one for photolithography since both operations happened in the same room. Volume of the nanofabrication lab is:

\[
37 \text{ ft} \times 16 \text{ ft} \times 10 \text{ ft} (\text{top floor}) + 13 \text{ ft} \times 13 \text{ ft} \times 10 \text{ ft} (\text{gowning area}) + 7 \text{ ft} \times 13 \text{ ft} \times 20 \text{ ft} (\text{stairs})
\]

\[
= 5920 \text{ cu.ft.} + 1690 \text{ cu.ft.} + 1820 \text{ cu.ft.} = 9430 \text{ cu.ft.}
\]

Volume allocated to the photolithography process = 9430/2 = 4715 cu.ft. Volume fraction with respect to the MBE lab = 4715/19320 = 0.24. Therefore, HVAC power consumption = 0.24 * 8.09 kW = 1.94 kW. Adding to this half of the fume hood HVAC contribution, we get: 1.94 kW + 1.35 kW = 3.29 kW. Over 24 hours, 3.29 kW * 24 h = 78.96 kWh.

5.2.4.2.8 HEPA filters

The HEPA filters’ energy consumption is shared between photolithography and metallization since the same fume hood was shared by both parts of the nano-fabrication lab. HEPA filter energy is thus equally shared. So, its contribution to metallization is same as its contribution to photolithography. Therefore, energy contribution from HEPA filters for metallization process = 0.065 kW. Over 24 hours, that is 0.065 kW*24 h = 1.56 kWh.

5.2.4.2.9 Human effort

An operator put in two hours for evaporation and 1 hour for ultrasonic lift-off process. Therefore, human effort amounted to 127 W*3 h = 381 Wh.

Table 22 summarizes the above information:
Table 22: Energy inventory for Metallization.

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporator</td>
<td>-</td>
<td>-</td>
<td>0.1154</td>
</tr>
<tr>
<td>Evaporator power supply</td>
<td>0.125</td>
<td>24</td>
<td>3.00</td>
</tr>
<tr>
<td>Evaporator turbo pumps</td>
<td>1.74</td>
<td>24</td>
<td>41.52</td>
</tr>
<tr>
<td>Evaporator chiller</td>
<td>4.50</td>
<td>24</td>
<td>108.00</td>
</tr>
<tr>
<td>Ultrasonic bath</td>
<td>0.073</td>
<td>1</td>
<td>0.073</td>
</tr>
<tr>
<td>Lighting</td>
<td>0.308</td>
<td>3</td>
<td>0.924</td>
</tr>
<tr>
<td>HVAC</td>
<td>3.29</td>
<td>24</td>
<td>78.96</td>
</tr>
<tr>
<td>HEPA filters</td>
<td>0.068</td>
<td>24</td>
<td>1.56</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>3</td>
<td>0.381</td>
</tr>
</tbody>
</table>

5.2.4.3 Annealing

This was the intermediate process between metallizing the front side and metallizing the back side of the sample. Therefore, this was categorized under ‘Fabrication’ even though it was conducted in the electrical characterization lab which is where device characteristics are obtained.

5.2.4.3.1 Nitrogen annealer

The power drawn by the nitrogen annealer was measured using the kill-a-watt energy meter to be 0.5kW. It remained constant throughout the 10 minutes of its use. Therefore, energy consumed:

\[ 0.5 \text{ kW} \times \frac{10}{60} \text{ h} = 0.083 \text{ kWh} \]  

(Equation 54)
5.2.4.3.2 Human effort

Human effort is required for 20 minutes for equipment setup and operation. Human effort:

\[ 127 \text{ W} \times \left( \frac{20}{60} \right) \text{ h} = 42.33 \text{ Wh} \]  

(Equation 55)

Overhead energy consumption for the nitrogen annealer equipment is not included in this section since this equipment takes up very little real estate in the electrical characterization lab. Accounting for the equipment’s overhead in this section will result in significantly low energy values (close to zero). The electrical characterization lab real estate was dominated by equipment whose overhead was accounted for in the ‘Device Characterization’ section (Section 5.2.6). The calculation included the floor area that accommodated the nitrogen annealer.

Table 23 below summarizes the above information:

**Table 23: Energy inventory for Annealing.**

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen annealer</td>
<td>0.50</td>
<td>0.167</td>
<td>0.0835</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>0.33</td>
<td>0.042</td>
</tr>
</tbody>
</table>

Consolidated data for Fabrication is summarized in Table 24 below:

**Table 24: Energy inventory for Fabrication.**

<table>
<thead>
<tr>
<th>Process</th>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photolithography</td>
<td>Oven</td>
<td>0.851</td>
<td>0.40</td>
<td>0.340</td>
</tr>
<tr>
<td>Photolithography</td>
<td>Spin Coater</td>
<td>-</td>
<td>-</td>
<td>0.004</td>
</tr>
<tr>
<td>Photolithography</td>
<td>Hot Plate</td>
<td>0.027</td>
<td>0.1</td>
<td>0.0027</td>
</tr>
<tr>
<td>Photolithography</td>
<td>Mask Aligner</td>
<td>-</td>
<td>-</td>
<td>0.004</td>
</tr>
</tbody>
</table>
## 5.2.5 Electronic packaging

This is the process that allows the operator to interface the device fabricated with external equipment to obtain device characteristics. A wire-bonding machine was used to connect wires to the contact pads and a heater was used to aid the bonding process.

### 5.2.5.1 Wire bonding machine
The wire-bonder’s power consumption was measured using the kill-a-watt meter and it was found to be an average of 26.7 W. The wire-bonder was used for about 30 minutes. So, the energy consumed = 26.7 W * 0.5 h = 13.35 Wh.

5.2.5.2 Heater

The heater drew an average of 141 W of power over the 30 minutes of its usage. Therefore, energy consumed = 141 W * 0.5 h = 70.5 Wh.

5.2.5.3 HVAC

Floor space for this equipment = 61.6 ft$^2$. Volume = 10 ft * 61.6 ft$^2$ = 616 ft$^3$. Volume fraction with respect to MBE lab = 616/19320 = 0.032. Power consumption = 8.09 kW * 0.032 = 0.259 kW. Over 48 hours that was allocated as the time period of equipment usage, HVAC energy contribution = 0.259 kW * 48h = 12.43 kWh.

5.2.5.4 Illumination

The space was small enough for one T-5 tube light to suffice. Energy from lighting = 28 W*0.5 h = 14 Wh.

5.2.5.5 Human effort

Energy from human effort = 0.127 kW * 0.5 h = 0.0635 kWh.

Table 25 shows the above data summarized:

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire-bonding machine</td>
<td>0.027</td>
<td>0.5</td>
<td>0.0135</td>
</tr>
<tr>
<td>Heater</td>
<td>0.141</td>
<td>0.5</td>
<td>0.0775</td>
</tr>
<tr>
<td>HVAC</td>
<td>0.26</td>
<td>48</td>
<td>12.48</td>
</tr>
<tr>
<td>Lighting</td>
<td>0.03</td>
<td>0.5</td>
<td>0.02</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>0.5</td>
<td>0.0635</td>
</tr>
</tbody>
</table>
5.2.6 Device characterization

This is an important phase in the research life cycle where the device created is tested for its performance. Device characteristics obtained in this phase include current-voltage (I-V) and capacitance-voltage (C-V) measurements, solar simulation, external quantum efficiency (EQE) measurements, deep level transient spectroscopy (DLTS) measurements, and Hall measurements. Since all equipment used in this last phase of the research were housed in the same laboratory, the overhead was shared and was thus calculated once, representing all.

5.2.6.1 I-V C-V Measurements

For obtaining I-V and C-V curves, several Keithley instruments were used. All the units run simultaneously for three hours. Each equipment’s power draw was measured using the kill-a-watt™ meter.

5.2.6.1.1 Source measure unit

The source measure unit, also called the generator, drew 127W. Energy =

\[127 \text{ W} \times 3 \text{ h} = 381 \text{ Wh}\]  
(Equation 56)

5.2.6.1.2 Quasi-static capacitance meter

The quasi-static capacitance meter, also called the I-V meter, showed 255 W of power drawn. Energy =

\[255 \text{ W} \times 3 \text{ h} = 765 \text{ Wh}\]  
(Equation 57)

5.2.6.1.3 Voltage source

The voltage source showed 73 W of power drawn. Energy =

\[73 \text{ W} \times 3 \text{ h} = 219 \text{ Wh}\]  
(Equation 58)

5.2.6.1.4 C-V analyzer

The C-V analyzer showed 195 W of power drawn. Energy =
195 W*3 h = 585 Wh \quad \text{(Equation 59)}

5.2.6.1.5 Computer

The desktop computer was estimated to consume the same as other desktops, i.e. 73.97 W while in operation, and 21.13 W while in sleep mode. Here, the computer was ON for 3 hours, and in sleep mode for 48 hours. Therefore, energy consumed =

\[(73.97 \text{ W} \times 3 \text{ h}) + (21.13 \text{ W} \times 48 \text{ h}) = 1236.15 \text{ Wh} \quad \text{(Equation 60)}\]

5.2.6.1.6 Human effort

Human effort =

\[127 \text{ W} \times 3 \text{ h} = 381 \text{ Wh} \quad \text{(Equation 61)}\]

The above data for I-V C-V measurements is summarized below in Table 26:

**Table 26: Energy inventory for I-V C-V measurement.**

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source measure unit</td>
<td>0.127</td>
<td>3</td>
<td>0.381</td>
</tr>
<tr>
<td>Quasi static capacitance meter</td>
<td>0.255</td>
<td>3</td>
<td>0.765</td>
</tr>
<tr>
<td>Voltage source</td>
<td>0.073</td>
<td>3</td>
<td>0.219</td>
</tr>
<tr>
<td>C-V analyzer</td>
<td>0.195</td>
<td>3</td>
<td>0.585</td>
</tr>
<tr>
<td>Computer</td>
<td>-</td>
<td>-</td>
<td>1.24</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>3</td>
<td>0.381</td>
</tr>
</tbody>
</table>

5.2.6.2 Solar Simulation

Solar simulation required only one equipment, an air mass (AM) 1.5 solar simulator, and a computer.
5.2.6.2.1 Solar simulator

Power drawn by the solar simulator was measured and found to be 110 W. This equipment was operated for 2 hours. Therefore energy consumed =

\[ 110 \text{ W} \times 2 \text{ h} = 220 \text{ Wh} \]  
(Equation 62)

5.2.6.2.2 Computer

The computer was used for 2 hours along with the solar simulator, and it was left idle for 48 hours until the next usage of the simulator. Therefore, energy consumed by the computer:

\[(73.97 \text{ W} \times 2 \text{ h}) + (21.13 \text{ W} \times 48 \text{ h}) = 1162.18 \text{ Wh} \]  
(Equation 63)

5.2.6.2.3 Human effort

Human effort of 2 hours of equipment operation amounted to

\[ 127 \text{ W} \times 2 \text{ h} = 254 \text{ Wh} \]  
(Equation 64)

The above data is tabulated in Table 27 below:

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar simulator</td>
<td>0.110</td>
<td>2</td>
<td>0.220</td>
</tr>
<tr>
<td>Computer</td>
<td>-</td>
<td>-</td>
<td>1.16</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>2</td>
<td>0.254</td>
</tr>
</tbody>
</table>

5.2.6.3 EQE Measurements

5.2.6.3.1 EQE measurement instruments

For measuring the external quantum efficiency of the sample solar cell, a number of equipment was used that were grouped into a single unit that we referred to as the EQE measurement instruments. The instruments included are xenon lamps, power supplies for the
lamps, modulator, monochromator, computer, and a vacuum pump. The entire unit was measured by the manufacturer’s technical support representative. The reported power consumption was 650 W. The equipment setup was used over 3 hours. Therefore, total energy consumption =

\[ 650 \text{ W} \times 3 \text{ h} = 1950 \text{ Wh} \quad \text{(Equation 65)} \]

5.2.6.3.2 Chiller

A chiller was also required for the equipment. The chiller’s power draw was also measured by the technical support specialist to be 100 W. Over 3 hours, that amounted to

\[ 100 \text{ W} \times 3 \text{ h} = 300 \text{ Wh} \quad \text{(Equation 66)} \]

5.2.6.3.3 Temperature controller

The temperature controller’s power draw was also measured by the technical support specialist. Power drawn = 50 W. Energy consumed over 3 hours =

\[ 50 \text{ W} \times 3 \text{ h} = 150 \text{ Wh} \quad \text{(Equation 67)} \]

5.2.6.3.4 Human effort

Human effort for EQE measurements for 3 hours =

\[ 127 \text{ W} \times 3 \text{ h} = 381 \text{ Wh} \quad \text{(Equation 68)} \]

Table 28 below summarizes the above information:

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQE measurement instruments</td>
<td>0.65</td>
<td>3</td>
<td>1.95</td>
</tr>
<tr>
<td>Chiller</td>
<td>0.100</td>
<td>3</td>
<td>0.300</td>
</tr>
<tr>
<td>Temperature controller</td>
<td>0.050</td>
<td>3</td>
<td>0.150</td>
</tr>
<tr>
<td>Human effort</td>
<td>0.127</td>
<td>3</td>
<td>0.381</td>
</tr>
</tbody>
</table>
5.2.6.4 DLTS Measurement

5.2.6.4.1 SULA spectrometer

For deep level transient spectroscopy (DLTS), a SULA spectrometer was used and a supporting vacuum pump. The spectrometer measured a power consumption of 144W. This equipment was run overnight. In this case, it was run for 32 hours. For this time period, the energy consumption was

\[ 144 \text{ W} \times 32 \text{ h} = 4608 \text{ Wh} \]  

(Equation 69)

5.2.6.4.2 Vacuum pump

The vacuum pump was Edwards RV-8 8200. This was the same model as the one used for photoluminescence. Modifying the time period in Table 13 for the purpose of DLTS, we got Table 29 below:

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand by</td>
<td>0.0179</td>
<td>16</td>
<td>0.2864</td>
</tr>
<tr>
<td>Roughing pump</td>
<td>0.395</td>
<td>0.083</td>
<td>0.033</td>
</tr>
<tr>
<td>Fine pump</td>
<td>0.381</td>
<td>32</td>
<td>12.192</td>
</tr>
<tr>
<td>Shutdown</td>
<td>0.290</td>
<td>0.167</td>
<td>0.048</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12.5594</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Therefore, total energy consumed by the vacuum pump = 12.56 kWh.

5.2.6.4.3 Human effort

Only four hours of human supervision was required. Human effort to conduct DLTS =

\[ 127 \text{ W} \times 4 \text{ h} = 508 \text{ Wh} \]  

(Equation 70)

Above data for DLTS is summarized in Table 30:
Table 30: Energy inventory for DLTS.

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SULA spectrometer</td>
<td>0.144</td>
<td>32</td>
<td>4.608</td>
</tr>
<tr>
<td>Vacuum pump</td>
<td>-</td>
<td>-</td>
<td>12.559</td>
</tr>
<tr>
<td>Human effort</td>
<td>.127</td>
<td>4</td>
<td>0.508</td>
</tr>
</tbody>
</table>

5.2.6.5 Hall Effect Measurement

Hall Effect measurement included the use of a magnet, a magnetometer, and a compressor. Other equipment that was also needed was grouped under Hall Effect instruments. It included a Keithley 220 current source, a Keithley 2182 nanovoltmeter, a Keithley switch card 7001, a 340 Lake Shore temperature controller, and a Kepko bipolar power supply. Hall measurements took 4 hours.

5.2.6.5.1 Magnet

The power consumption of the magnet (9707A model) could not be measured as it was not a 120 V power source. The power consumption was taken from its manual to be 300 W [42]. This meant energy consumed over 4 hours of operation =

\[ 300 \text{ W}*4 \text{ h} = 1200 \text{ Wh} \]  

(Equation 71)

5.2.6.5.2 Magnetometer

The Lake Shore magnetometer’s power consumption was measured using the kill-a-watt meter and it was found to consume 33 W of power. Energy over four hours is therefore,

\[ 33 \text{ W}*4 \text{ h} = 132 \text{ Wh} \]  

(Equation 72)
The compressor (Edwards RV-8 8200) used here was the same as the one used for photoluminescence and DLTS. Table 13 is modified below as Table 31 for breakdown of vacuum pump energy consumption over time.

### Table 31: Breakdown for vacuum pump energy consumption.

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand by</td>
<td>0.0179</td>
<td>44</td>
<td>0.7876</td>
</tr>
<tr>
<td>Roughing pump</td>
<td>0.395</td>
<td>0.083</td>
<td>0.033</td>
</tr>
<tr>
<td>Fine pump</td>
<td>0.381</td>
<td>4</td>
<td>1.524</td>
</tr>
<tr>
<td>Shutdown</td>
<td>0.290</td>
<td>0.167</td>
<td>0.048</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.393</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.6.5.4 Hall Effect instruments

The other instruments grouped under *Hall Effect instruments* were measured using the kill-a-watt meter. Power drawn = 96 W. Energy consumed =

\[ 96 \text{ W} \times 4 \text{ h} = 384 \text{ Wh} \quad \text{(Equation 73)} \]

5.2.6.5.5 Computer

The computer was ON for 4 h and idle for 44 h. Energy drawn:

\[ (74 \text{ W} \times 4 \text{ h}) + (21.13 \text{ W} \times 44 \text{ h}) = 296 \text{ Wh} + 929.72 \text{ Wh} = 1225.72 \text{ Wh} \quad \text{(Equation 74)} \]

5.2.6.5.6 Human effort

Human effort of 4 hours draws

\[ 127 \text{ W} \times 4 \text{ h} = 508 \text{ Wh} \quad \text{(Equation 75)} \]

The above information was summarized in Table 32.
Table 32: Energy inventory for Hall Effect measurement.

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet</td>
<td>0.300</td>
<td>4</td>
<td>1.200</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>0.033</td>
<td>4</td>
<td>0.132</td>
</tr>
<tr>
<td>Compressor</td>
<td>-</td>
<td>-</td>
<td>2.393</td>
</tr>
<tr>
<td>Hall effect instruments</td>
<td>0.096</td>
<td>4</td>
<td>0.384</td>
</tr>
<tr>
<td>Computer</td>
<td>-</td>
<td>-</td>
<td>1.226</td>
</tr>
<tr>
<td>Human effort</td>
<td>.127</td>
<td>4</td>
<td>0.508</td>
</tr>
</tbody>
</table>

5.2.6.6 Device characterization overhead

5.2.6.6.1 Illumination

The electrical characterization lab had 14 light tubes.

\[28 \text{ W} \times 14 \text{ tubes} = 392 \text{ W}\]  \hspace{1cm} (Equation 76)

Over 4.5 hours,

\[392 \text{ W} \times 4.5 \text{ h} = 1764 \text{ Wh}\]  \hspace{1cm} (Equation 77)

5.2.6.6.2 HVAC

Volume of the electrical characterization lab was 28 ft x 22 ft x 10 ft = 6160 cu.ft. Volume of electronic packaging station was included in this (616 cu.ft.). Therefore, effective volume = 6160 cu.ft. – 616 cu.ft. = 5544 cu.ft. Volume fraction compared to the MBE lab = \(5544/19320 = 0.287\). HVAC power for this volume =

\[8.09 \text{ kW} \times 0.287 = 2.32 \text{ kW}\]  \hspace{1cm} (Equation 78)

Over 48 hours

\[2.32 \text{ kW} \times 48 \text{ h} = 111.46 \text{ kWh}\]  \hspace{1cm} (Equation 79)

The above information is summarized in Table 33.
Table 33: Energy inventory for Device characterization overhead.

<table>
<thead>
<tr>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>0.392</td>
<td>4.5</td>
<td>1.764</td>
</tr>
<tr>
<td>HVAC</td>
<td>2.322</td>
<td>48</td>
<td>111.46</td>
</tr>
</tbody>
</table>

The energy consumption for all device characterization methods and overhead is consolidated in Table 34 below:

Table 34: Energy inventory for device characterization.

<table>
<thead>
<tr>
<th>Process</th>
<th>Equipment/Operation</th>
<th>Power draw (kW)</th>
<th>Duration (h)</th>
<th>Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-V C-V Measurements</td>
<td>Source measure unit</td>
<td>0.127</td>
<td>3</td>
<td>0.381</td>
</tr>
<tr>
<td>I-V C-V Measurements</td>
<td>Quasi static capacitance meter</td>
<td>0.255</td>
<td>3</td>
<td>0.765</td>
</tr>
<tr>
<td>I-V C-V Measurements</td>
<td>Voltage source</td>
<td>0.073</td>
<td>3</td>
<td>0.219</td>
</tr>
<tr>
<td>I-V C-V Measurements</td>
<td>C-V analyzer</td>
<td>0.195</td>
<td>3</td>
<td>0.595</td>
</tr>
<tr>
<td>I-V C-V Measurements</td>
<td>Computer</td>
<td>-</td>
<td>-</td>
<td>1.24</td>
</tr>
<tr>
<td>I-V C-V Measurements</td>
<td>Human effort</td>
<td>0.127</td>
<td>3</td>
<td>0.381</td>
</tr>
<tr>
<td>Solar simulation</td>
<td>Solar simulator</td>
<td>0.110</td>
<td>2</td>
<td>0.220</td>
</tr>
<tr>
<td>Solar simulation</td>
<td>Computer</td>
<td>-</td>
<td>-</td>
<td>1.16</td>
</tr>
<tr>
<td>Solar simulation</td>
<td>Human effort</td>
<td>0.127</td>
<td>2</td>
<td>0.254</td>
</tr>
<tr>
<td>EQE</td>
<td>EQE measurement instruments</td>
<td>0.65</td>
<td>3</td>
<td>1.95</td>
</tr>
<tr>
<td>EQE</td>
<td>Chiller</td>
<td>0.100</td>
<td>3</td>
<td>0.300</td>
</tr>
<tr>
<td>EQE</td>
<td>Temperature controller</td>
<td>0.050</td>
<td>3</td>
<td>0.150</td>
</tr>
<tr>
<td>EQE</td>
<td>Human effort</td>
<td>0.127</td>
<td>3</td>
<td>0.381</td>
</tr>
<tr>
<td>DLTS</td>
<td>SULA spectrometer</td>
<td>0.144</td>
<td>32</td>
<td>4.608</td>
</tr>
<tr>
<td>Process</td>
<td>Equipment/Operation</td>
<td>Power draw (kW)</td>
<td>Duration (h)</td>
<td>Energy (kWh)</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------</td>
<td>-----------------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>DLTS</td>
<td>Vacuum pump</td>
<td>-</td>
<td>-</td>
<td>12.559</td>
</tr>
<tr>
<td>DLTS</td>
<td>Human effort</td>
<td>.127</td>
<td>4</td>
<td>0.508</td>
</tr>
<tr>
<td>Hall measurements</td>
<td>Magnet</td>
<td>0.300</td>
<td>4</td>
<td>1.200</td>
</tr>
<tr>
<td>Hall measurements</td>
<td>Magnetometer</td>
<td>0.033</td>
<td>4</td>
<td>0.132</td>
</tr>
<tr>
<td>Hall measurements</td>
<td>Compressor</td>
<td>-</td>
<td>-</td>
<td>2.393</td>
</tr>
<tr>
<td>Hall measurements</td>
<td>Hall effect instruments</td>
<td>0.096</td>
<td>4</td>
<td>0.384</td>
</tr>
<tr>
<td>Hall measurements</td>
<td>Computer</td>
<td>-</td>
<td>-</td>
<td>1.226</td>
</tr>
<tr>
<td>Hall measurements</td>
<td>Human effort</td>
<td>.127</td>
<td>4</td>
<td>0.508</td>
</tr>
<tr>
<td>Overhead</td>
<td>Lighting</td>
<td>0.392</td>
<td>4.5</td>
<td>1.764</td>
</tr>
<tr>
<td>Overhead</td>
<td>HVAC</td>
<td>2.322</td>
<td>48</td>
<td>111.46</td>
</tr>
</tbody>
</table>

Table 35 consolidates the entire inventory for this case study.

**Table 35: Complete energy inventory for the test-bed system.**

<table>
<thead>
<tr>
<th>Process Category</th>
<th>Process</th>
<th>Equipment/ Operation</th>
<th>Energy consumed (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeling and Simulation</td>
<td>Computer use</td>
<td></td>
<td>0.0739</td>
</tr>
<tr>
<td>Modeling and Simulation</td>
<td>Human effort</td>
<td></td>
<td>0.127</td>
</tr>
<tr>
<td>Modeling and Simulation</td>
<td>Lighting</td>
<td></td>
<td>0.112</td>
</tr>
<tr>
<td>Modeling and Simulation</td>
<td>HVAC</td>
<td></td>
<td>0.507</td>
</tr>
<tr>
<td>Material Growth by MBE</td>
<td>MBE equipment during growth</td>
<td></td>
<td>79.1</td>
</tr>
<tr>
<td>Material Growth by MBE</td>
<td>MBE equipment at idle state</td>
<td></td>
<td>36.4</td>
</tr>
<tr>
<td>Material Growth by MBE</td>
<td>Lighting</td>
<td></td>
<td>13.86</td>
</tr>
<tr>
<td>Material Growth by MBE</td>
<td>HVAC</td>
<td></td>
<td>194.15</td>
</tr>
<tr>
<td>Process Category</td>
<td>Process</td>
<td>Equipment/ Operation</td>
<td>Energy consumed (kWh)</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------</td>
<td>----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Material Growth by MBE</td>
<td>HEPA filters</td>
<td></td>
<td>6.24</td>
</tr>
<tr>
<td>Material Growth by MBE</td>
<td>Human effort</td>
<td></td>
<td>0.711</td>
</tr>
<tr>
<td>Material Char.</td>
<td>PL</td>
<td>InGaAs CCD detector</td>
<td>0.348</td>
</tr>
<tr>
<td>Material Char.</td>
<td>PL</td>
<td>Chiller</td>
<td>0.1625</td>
</tr>
<tr>
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</tr>
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<td>Laser</td>
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<td>Temperature controller</td>
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</tr>
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<td>PL</td>
<td>Compressor</td>
<td>3.26</td>
</tr>
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<td>Material Char.</td>
<td>PL</td>
<td>Illumination</td>
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</tr>
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<td>Material Char.</td>
<td>PL</td>
<td>Computer</td>
<td>0.26</td>
</tr>
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<td>PL</td>
<td>Human effort</td>
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</tr>
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<td>PL</td>
<td>HVAC</td>
<td>10.72</td>
</tr>
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<td>Material Char.</td>
<td>TEM Sample Prep.</td>
<td>Hot plate</td>
<td>0.026</td>
</tr>
<tr>
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<td>Microscope</td>
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<td>TEM Sample Prep.</td>
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<td>TEM Sample Prep.</td>
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<td>Material Char.</td>
<td>TEM Sample Prep.</td>
<td>Lighting</td>
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</tr>
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<td>TEM Sample Prep.</td>
<td>Human effort</td>
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</tr>
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<td>TEM Sample Prep.</td>
<td>HVAC</td>
<td>9.28</td>
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<tr>
<td>------------------</td>
<td>---------------</td>
<td>------------------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Material Char.</td>
<td>TEM</td>
<td>TEM analysis</td>
<td>20.7</td>
</tr>
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<td>Computer use</td>
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</tr>
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<td>TEM</td>
<td>Human effort</td>
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</tr>
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<td>Lighting</td>
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<td>TEM</td>
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</tr>
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<td>XRD</td>
<td>XRD analysis</td>
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</tr>
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<td>XRD</td>
<td>Human Effort</td>
<td>0.042</td>
</tr>
<tr>
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<td>XRD</td>
<td>HVAC</td>
<td>11.2</td>
</tr>
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<td>Lighting</td>
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</tr>
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</tr>
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<td>Human Effort</td>
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</tr>
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<td>HVAC</td>
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</tr>
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<td>Oven</td>
<td>0.340</td>
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<td>Photolithography</td>
<td>Spin Coater</td>
<td>0.004</td>
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<td>Photolithography</td>
<td>Hot Plate</td>
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<td>Photolithography</td>
<td>Mask Aligner</td>
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<td>Photolithography</td>
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<td>0.0055</td>
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<td>Photolithography</td>
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<td>Process Category</td>
<td>Process</td>
<td>Equipment/ Operation</td>
<td>Energy consumed (kWh)</td>
</tr>
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<td>------------------</td>
<td>-----------------</td>
<td>-------------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Photolithography</td>
<td>HVAC</td>
<td>78.96</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Photolithography</td>
<td>HEPA filters</td>
<td>1.56</td>
</tr>
<tr>
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<td>Photolithography</td>
<td>Human effort</td>
<td>0.254</td>
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<td>Metallization</td>
<td>Evaporator</td>
<td>0.1154</td>
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<td>Fabrication</td>
<td>Metallization</td>
<td>Evaporator power supply</td>
<td>3.00</td>
</tr>
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<td>Fabrication</td>
<td>Metallization</td>
<td>Evaporator turbo pumps</td>
<td>41.52</td>
</tr>
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<td>Metallization</td>
<td>Evaporator chiller</td>
<td>108.00</td>
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<td>Metallization</td>
<td>Ultrasonic bath</td>
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</tr>
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<td>Lighting</td>
<td>0.924</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Metallization</td>
<td>HVAC</td>
<td>78.96</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Metallization</td>
<td>HEPA filters</td>
<td>1.56</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Metallization</td>
<td>Human effort</td>
<td>0.381</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Annealing</td>
<td>Nitrogen annealer</td>
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</tr>
<tr>
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<td>Annealing</td>
<td>Human effort</td>
<td>0.042</td>
</tr>
<tr>
<td>Electronic Packaging</td>
<td>Wire-bonding machine</td>
<td></td>
<td>0.0135</td>
</tr>
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<td>Heater</td>
<td></td>
<td>0.075</td>
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<td>HVAC</td>
<td></td>
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<td>Lighting</td>
<td></td>
<td>0.02</td>
</tr>
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<td>Human effort</td>
<td></td>
<td>0.0635</td>
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<td>Device Char.</td>
<td>I-V C-V Measurements</td>
<td>Source measure unit</td>
<td>0.381</td>
</tr>
<tr>
<td>Process Category</td>
<td>Process</td>
<td>Equipment/ Operation</td>
<td>Energy consumed (kWh)</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------</td>
<td>--------------------------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Device Char.</td>
<td>I-V C-V Measurements</td>
<td>Quasi static capacitance meter</td>
<td>0.765</td>
</tr>
<tr>
<td>Device Char.</td>
<td>I-V C-V Measurements</td>
<td>Voltage source</td>
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</tr>
<tr>
<td>Device Char.</td>
<td>I-V C-V Measurements</td>
<td>C-V analyzer</td>
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</tr>
<tr>
<td>Device Char.</td>
<td>I-V C-V Measurements</td>
<td>Computer</td>
<td>1.24</td>
</tr>
<tr>
<td>Device Char.</td>
<td>I-V C-V Measurements</td>
<td>Human effort</td>
<td>0.381</td>
</tr>
<tr>
<td>Device Char.</td>
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<td>Solar simulator</td>
<td>0.220</td>
</tr>
<tr>
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<td>Solar simulation</td>
<td>Computer</td>
<td>1.16</td>
</tr>
<tr>
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<td>Solar simulation</td>
<td>Human effort</td>
<td>0.254</td>
</tr>
<tr>
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<td>EQE</td>
<td>EQE measurement instruments</td>
<td>1.95</td>
</tr>
<tr>
<td>Device Char.</td>
<td>EQE</td>
<td>Chiller</td>
<td>0.300</td>
</tr>
<tr>
<td>Device Char.</td>
<td>EQE</td>
<td>Temperature controller</td>
<td>0.150</td>
</tr>
<tr>
<td>Device Char.</td>
<td>EQE</td>
<td>Human effort</td>
<td>0.381</td>
</tr>
<tr>
<td>Device Char.</td>
<td>DLTS</td>
<td>SULA spectrometer</td>
<td>4.608</td>
</tr>
<tr>
<td>Device Char.</td>
<td>DLTS</td>
<td>Vacuum pump</td>
<td>12.559</td>
</tr>
<tr>
<td>Device Char.</td>
<td>DLTS</td>
<td>Human effort</td>
<td>0.508</td>
</tr>
<tr>
<td>Device Char.</td>
<td>Hall measurements</td>
<td>Magnet</td>
<td>1.200</td>
</tr>
<tr>
<td>Device Char.</td>
<td>Hall measurements</td>
<td>Magnetometer</td>
<td>0.132</td>
</tr>
<tr>
<td>Device Char.</td>
<td>Hall measurements</td>
<td>Compressor</td>
<td>2.393</td>
</tr>
<tr>
<td>Device Char.</td>
<td>Hall measurements</td>
<td>Hall effect instruments</td>
<td>0.384</td>
</tr>
<tr>
<td>Device Char.</td>
<td>Hall measurements</td>
<td>Computer</td>
<td>1.226</td>
</tr>
</tbody>
</table>
This section on the life cycle inventory analysis of the test bed system explained the data collection process and listed the raw data obtained. The next section will analyze the data collected and assess the impact of each process on the total energy demand.

### 5.3 LIFE CYCLE IMPACT ASSESSMENT

The chosen impact of interest for this study was total energy demand. The total energy demand for researching one sample using the given process flow was found to be 937 kWh. Table 36 and Figure 22 below show the breakdown of this energy consumption by process category. The bars highlighted red and orange are explored further.

**Table 36: Energy breakdown by process category.**

<table>
<thead>
<tr>
<th>Process category</th>
<th>Energy (kWh)</th>
<th>Percent of total energy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeling and Simulation</td>
<td>0.8</td>
<td>0.09</td>
</tr>
<tr>
<td>Material Growth</td>
<td>330.5</td>
<td>35.27</td>
</tr>
<tr>
<td>Material Characterization</td>
<td>132.0</td>
<td>14.09</td>
</tr>
<tr>
<td>Fabrication</td>
<td>316.6</td>
<td>33.79</td>
</tr>
<tr>
<td>Electronic Packaging</td>
<td>12.7</td>
<td>1.36</td>
</tr>
<tr>
<td>Device Characterization</td>
<td>144.7</td>
<td>15.44</td>
</tr>
<tr>
<td>Total</td>
<td>937</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 22: Breakdown of energy consumption by process category.

From Figure 22 it can be seen that both material growth and fabrication process categories dominate the energy consumption of this research process. Both of these process categories are expanded into their sub-processes so that energy hot-spots can be identified. Figures 23 and 24 show the breakdown for material growth (highlighted red) and fabrication (highlighted orange), respectively.

Figure 23: Energy components of material growth.

It can be observed from Figure 23 that HVAC dominates energy consumption in material growth phase with 194.15 kWh of consumption.
Figure 24: Energy components of fabrication.

Metallization (highlighted green) is further divided into its components in Figure 25.

Figure 25: Energy consumption of metallization components.

The evaporator chillers have the highest energy concentration in the fabrication phase with 108 kWh (from Figure 25) consumption out of 317 kWh (from Table 36). This is 34% of the energy used for fabrication. Looking back at Section 5.2.4.2.4, it is evident that the chillers consume a lot of power since they are kept ON 24 hours a day, seven days a week, and they draw a constant 4.5 kW. The second highest energy demand among metallization components is the
HVAC energy consumption of 78.96 kWh. This is mainly due to its inherent high power requirement and the fact that it runs non-stop.

Such top-down dissections are helpful in narrowing down to a particular energy component within a particular phase of the process flow. But in order to compare all items together at the highest granularity level without any category filters, a bottom-up approach is presented. For this, a single master graph containing all process items are created without regard to the phase of the process flow that the items belong to. This graph is then sorted by energy value of each component. For ease of visual display, this section presents the master graph in the form of three ordered graphs that can be appended one after the other to form the master graph.

The first graph (Figure 24) lists items that consume more than 1 kWh of energy. The second graph (Figure 25) lists items consuming between 1 kWh and 0.1 kWh. And the third graph (Figure 26) lists the remaining items that consume less than 0.1 kWh. This way it is easier to compare the individual items regardless which process category they belong to.

See Figures 26, 27, and 28 below (next page).

It is no surprise that both Figures 24 and 25 make it clear that HVAC energy consumption for the MBE facility is the highest energy consumption among all operations listed for this case study. However, the second highest energy consumption according to Figure 26 is the HVAC operation for the electrical characterization lab, which was not depicted in the earlier graphs (Figures 22-25). This is because other operations for device characterization consumed less energy relative to operations for material growth and fabrication. Material growth processes and fabrication processes each consume more energy than the collective energy consumption of the device characterization phase. Individually, HVAC for material growth tops the list, followed by HVAC for electrical characterization lab, and evaporator chiller for metallization.
Figure 26: Energy consumption of operations/equipment consuming more than 1 kWh.
Figure 27: Energy consumption of operations consuming between 0.1 kWh and 1 kWh.
Figure 28: Energy consumption of operations/equipment consuming less than 0.1 kWh.

The chiller’s high energy consumption (item 3 in Table 37) was also apparent from Figure 23. It is therefore clear that both methods of data analysis must be used to draw conclusions for clarity.

The top 10 individual items consuming maximum energy is listed below in Table 37 and their section references are provided.
Table 37: Top 10 energy intensive operations for this test-bed system.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Item/Operation</th>
<th>Energy consumed (kWh)</th>
<th>% of total energy</th>
<th>Section reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HVAC for MBE lab</td>
<td>194.15</td>
<td>20.72</td>
<td>5.2.1.4</td>
</tr>
<tr>
<td>2</td>
<td>HVAC for device characterization lab</td>
<td>111.46</td>
<td>11.90</td>
<td>5.2.6.6.2</td>
</tr>
<tr>
<td>3</td>
<td>Chiller for e-beam evaporator</td>
<td>108</td>
<td>11.53</td>
<td>5.2.4.2.4</td>
</tr>
<tr>
<td>4</td>
<td>MBE equipment during growth</td>
<td>79.1</td>
<td>8.44</td>
<td>5.2.1.1</td>
</tr>
<tr>
<td>5</td>
<td>HVAC for photolithography lab</td>
<td>78.96</td>
<td>8.43</td>
<td>5.2.4.1.7</td>
</tr>
<tr>
<td>6</td>
<td>HVAC for metallization lab</td>
<td>78.96</td>
<td>8.43</td>
<td>5.2.4.2.7</td>
</tr>
<tr>
<td>7</td>
<td>Sample growth for AFM</td>
<td>55.1</td>
<td>5.88</td>
<td>5.2.3.5.5</td>
</tr>
<tr>
<td>8</td>
<td>Turbo pumps for e-beam evaporator</td>
<td>41.52</td>
<td>4.43</td>
<td>5.2.4.2.3</td>
</tr>
<tr>
<td>9</td>
<td>MBE equipment at idle state</td>
<td>36.4</td>
<td>3.88</td>
<td>5.2.1.2</td>
</tr>
<tr>
<td>10</td>
<td>TEM analysis</td>
<td>20.7</td>
<td>2.21</td>
<td>5.2.3.3.1</td>
</tr>
</tbody>
</table>

In this section, results were shown using two different approaches. The next section draws conclusions based on these results and interprets the conclusions drawn with respect to the intended purpose of the study as established in the goal and scope sections of this analysis.

5.4 INTERPRETATION

This section interprets the results obtained in the impact assessment section in order to connect the findings from the study with the goal and scope of the study. To do so, the impact
assessment results are analyzed and evaluated alongside the goal and scope definition and limitations of the study. Recommendations are presented from the conclusions drawn.

The goal of this study was twofold:

1. To quantify total energy required to research the growth and fabrication of a quantum wire-based GaAs PV cell, and
2. To identify the stages in the research process of this PV technology that consume most energy

5.4.1 Total energy demand

The total energy required to grow and fabricate a 5 mm x 5 mm sample of solar cell was found to be 937 kWh. This is the non-recoverable cost of this research. The output from this research is not a tangible product, but intellectual property that is communicated to the scientific community mostly through academic research papers. Therefore, the reference flow of a 5 mm x 5 mm sample of PV cell is for internal measurement purposes only, and not a metric for comparison. The functional unit of efficiency may be used for comparing to similar systems.

5.4.2 Energy-intensive processes

It is clear from Figure 22 and Table 36 that the material growth phase dominates the energy demand by consuming 35.27% of the total energy required. The HVAC energy cost is discussed further in Section 5.4.2.1.

The other energy-intensive process is fabrication of the device. This phase of the technology’s research life cycle involves several sequential steps. One of these steps is metallization of gold on either side of the sample. The metal is evaporated on to the sample using an e-beam evaporator. A chilled water system is used for heat management that consumes 108
103 kWh of energy (Figure 25). The chiller runs even when the evaporator is not in use. For a more energy efficient process flow, this issue must be addressed.

HVAC for the device characterization lab is also energy intensive. It consumes 111.46 kWh of energy, which is 11.90% of the total energy consumed. It can be observed from Figures 26, 27, and 28 that most of the heating and cooling components consume maximum power.

5.4.2.1 HVAC

For this study, it is clear from Figure 24 that HVAC energy consumption, in general, is substantial. Nine out of ten HVAC contributions are listed among the top 20 (out of 91) energy consuming operations. All HVAC operations put together amount to 521.84 kWh. This is 56% of the total energy demand. This is a significant issue that must be addressed since this is an overhead cost and not a direct cost. Table 38 lists out the energy consumed by HVAC for each lab. The energy consumption is dependent on both power drawn and duration of use. Power drawn is directly proportional to the volume of the lab and whether or not there is a fume hood in the lab. Duration, in this case, is time period between two usages of the same equipment/lab.

Table 38: HVAC energy consumption for various labs.

<table>
<thead>
<tr>
<th>Lab/Process/Operation</th>
<th>Fume hood (Y/N)</th>
<th>Volume of lab (cu.ft.)</th>
<th>Power Use (kW) per sample</th>
<th>Time (h) per sample</th>
<th>Energy consumed (kWh) per sample</th>
<th>Duty cycle adjustment</th>
<th>% of total energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE lab</td>
<td>Yes</td>
<td>19320</td>
<td>16.179</td>
<td>12</td>
<td>194.15</td>
<td>194.15</td>
<td>20.72</td>
</tr>
<tr>
<td>Electrical characterization lab</td>
<td>No</td>
<td>6160</td>
<td>2.322</td>
<td>48</td>
<td>111.46</td>
<td>111.46</td>
<td>11.90</td>
</tr>
<tr>
<td>Photolithography lab</td>
<td>Yes</td>
<td>4715</td>
<td>3.29</td>
<td>24</td>
<td>78.96</td>
<td>78.96</td>
<td>8.43</td>
</tr>
<tr>
<td>Metallization lab</td>
<td>Yes</td>
<td>4715</td>
<td>3.29</td>
<td>24</td>
<td>78.96</td>
<td>78.96</td>
<td>8.43</td>
</tr>
</tbody>
</table>
Therefore, to reduce power consumption by HVAC, the volume of the facility should be as small as possible. To reduce duration of HVAC use accounted for one sample, the idle time of equipment between two uses must be reduced. HVAC energy demand for XRD lab is dominated by the 96 hours of time between two usages of the equipment even though its power consumption is relatively smaller than that of PL lab, electronic packaging station, and TEM lab. In other words, equipment should be utilized more often instead of being left idling.

5.4.2.2 Chiller for e-beam evaporator

Heat management of equipment that work at low temperatures is also energy demanding. The chiller used with the evaporator runs 24 hours a day, 7 days a week, and for this reason, it is among the top three energy intensive components. It consumes 108kWh of energy. This is a necessary component for the e-beam evaporator and therefore, cannot be eliminated. Instead, energy use may be optimized by sharing the resource more often.
5.4.2 Recommendations

As part of this LCA, following are some of the recommendations for improving energy payback time and energy return on investment of these emerging solar cells.

1. Facilities must be as compact as possible. This is in order to minimize HVAC energy consumption.

2. Equipment idle time must be minimized. This is because the overhead energy for keeping equipment idle is too high.

3. If equipment is idle for too long, the equipment does not have a good utilization factor and must be transferred to a place where it will be used more often. Research labs can cooperate and share equipment in order to better utilize resources.

5.4.3 Completeness check

All data that was intended to be collected was collected. Data that could have been included but could not be collected are mentioned in the assumptions and limitations sections (Sections 5.1.4 and 5.1.5) of the goal and scope definition.

5.4.4 Sensitivity check

Some of the sensitive data are:

- HVAC energy consumption: This can be easily affected by changes in the volume of the facility. However, such a change is not anticipated since volume is fixed and it was measured.

- Equipment idle time: This may vary from person to person since the data obtained were best estimates by users of the equipment. For instance, it may take one person 30 minutes to obtain an AFM read, while another person takes 45 minutes. Data given by one person may be an overestimation or underestimation for another person. This can be attributed to human-
relativity error. For instance, 1 hour of idle time for equipment may be considered too long for one user, and too short for another user. Data presented here are based on estimations made by some of the most experienced operators of the equipment.

5.4.5 Consistency check

The data collected and interpreted are as per the goal and scope defined earlier (Section 5.1). All data meet the data quality criteria mentioned earlier (Section 5.1.3).
CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 SUMMARY

The goal of this case study was to quantify the total energy demand of a research process involving an emerging PV technology and to identify energy intensive operations. This was accomplished using life cycle assessment methodology on a test-bed system. The emerging PV technology chosen was quantum wire based intermediate band solar cell (IBSC) and the test-bed system was the research process of designing and developing an InGaAs quantum wire based IBSC. The impact category of interest was the total energy demand of the system. The system was found to consume 937 kWh. For comparison, this is 83% of the average monthly household electricity consumption in Arkansas [43].

This case study for InGaAs quantum wire intermediate band solar cell revealed several energy intensive processes. The top three included the HVAC for the MBE lab, chiller for the e-beam evaporator, and HVAC for the electrical characterization lab. It was noted that all three equipment were support systems that maintained temperature. These components were run full time, regardless if the equipment they supported was being used or not. Operating a machine consumes much less energy per unit output than to keep the equipment online when not in use. It was thus concluded that equipment should not be left idling for too long as it is expensive (energy-wise) to do so. HVAC power was assumed to be directly proportional to the volume of the lab. Hence, facilities should be made as compact as possible to avoid energy expenditure on empty spaces.
6.2 FUTURE WORK

There is scope for future work to be based upon this case study. One may want to design a scaled up model suitable for mass production. This will, however, require numerous assumptions and approximations, such as the size of a batch and time period between consecutive uses of equipment. Key factors to consider in this case are as follows:

- A higher throughput MBE machine (either one that can process multiple wafers at a time, or multiple MBE machines running in parallel) may increase production rate by allowing for a more suitable (energy efficient) batch size of wafers for fabrication. Most “wet” methods of fabrication can be done in large batches but, to take advantage of a batch process, the MBE throughput must match the throughput of the fabrication process. The tradeoff is that the load on HVAC will increase if a bigger MBE machine is used.

- It is likely that a critical path method (CPM) analysis will show that the MBE operation is the critical activity in the production line. This is because most equipment are left at idle state while the MBE processes a single batch of solar cells.

- It will also be important to consider outsourcing some characterization services. Energy and cost analyses would complement each other and could constitute a project in industrial engineering. Finding the optimum batch size and number of equipment at each step in the process can be a worthwhile contribution, especially for those wanting to start a new business in this field.

One may take the life cycle assessment projection a step further by performing a life cycle inventory analysis on the materials used for this test-bed system and assessing its impact on the environment. Primary data that is collected will contribute to the vast database that most LCA practitioners depend on. Going further, the LCA may be complemented by the energy
analysis. The result could be a complete research life cycle analysis or the subset of a product’s life cycle analysis projection.

The model created for this case study can be reused for other similar systems with minor adjustments. For instance, other III-V solar cells that use similar processing techniques. By increasing the scope of this project, one can move toward a more holistic picture of the life cycle impact of emerging energy technologies to the environment. After comparing all environmental impacts (both positive and negative) one may endorse a technology to be truly sustainable and “green”.

An economic analysis of the research life cycle of a technology can aid in the formation of better economic policies for research institutes. For instance, the overhead energy cost of this test-bed system can be compared to the overhead (indirect) cost that is provided for by funding agencies. Such an analysis would pinpoint the root causes of imbalances in the economic cycle of a higher education system. This will also help funding agencies make better fund allocation decisions based on more accurate knowledge-based projections.

6.3 CONCLUSION

The intended purpose of this study is to make the academic community aware of the energy spent in research. The idea is to encourage a life-cycle thinking approach in the minds of researchers whose goal is to push the boundaries of science and technology. Though the process of research inherently involves non-recoverable costs including energy expenses, it must also be recognized as an area of improvement by optimizing energy consumption. This will not only make the life cycle of the product more energy efficient, it will also promote a healthier research life cycle where energy costs are properly accounted for in indirect costs of research. Such an approach will sustain new-material, new-technology research for a very long time. Foresight into
energy consumption at the design stage will optimize future facility design. Optimized research processes will then lead to relative ease in commercialization of such research.
References


Appendix A: Description of research for popular publication

Researchers Quantify Energy Cost of Energy Research

Researchers at the University of Arkansas, Fayetteville have taken an interesting approach to renewable energy research. It is being called the ‘Energy Paradox’. Why is it a paradox? It is a paradox because, according to one of the researchers, “a lot of non-renewable energy is being used to research the potential capability of renewable energy technologies.” Ms. Shilpi Mukherjee, master’s student of Microelectronics-Photonics program, has studied this energy paradox with academic advisor Dr. Ajay P. Malshe, distinguished professor in department of Mechanical Engineering.

National databases maintain a log of the carbon dioxide emissions from all power plants in the United States. Flint Creek, the power plant that supplies electricity to most areas in Northwest Arkansas, emits more than 2000lbs of carbon dioxide for every megawatt-hour (MWh) generated. That is the source of our grid electricity and it is an immense environmental burden that needs to be addressed.

![Figure A.1: PV installation capacities [1].](image-url)
Society has been looking at many clean energy generation methods for quite some time. After decades of research investments, solar cells have started to gain traction in the energy market since 2000 and the manufacturing of solar cells is dominated by China. Figure A.1 shows the pace of this growing industry by country [1].

What’s obvious is the growing installation capacity. What’s not obvious is what will happen to the solar panels once they reach their end of life. Will they be incinerated? Will they be landfilled? Or will they be recycled? Most consumers dispose of their solar cell devices as general trash. The materials that make up most commercial solar panels today include silicon, aluminum, glass, copper, tin-lead pastes, etc. These solar cells end up in the soil and harm the environment just like electronic wastes (e-waste). Figure A.2 shows e-waste piles in Indonesia [2]. Materials in these waste products are potentially toxic to human beings.

Figure A.2: E-waste in Bali, Indonesia [2].
Someone needs to look at the solar industry with a broader view. The researchers claim, “We need to assess the environmental impact of these products from their cradle to their grave to get a holistic picture of their effects on our eco-system.” Dr. Malshe noted that life cycle analysis is the way to accomplish this.

Life cycle analysis or life cycle assessment is a tool that captures all the pros and cons of a system with respect to the environment. It is an ISO-established standard that assesses the environmental impact of a product throughout its life cycle. A typical product’s life cycle includes raw material acquisition, material processing, device fabrication, transportation, assembly, use, and disposal as shown in Figure A.3 [3].

Existing databases compile data on life cycle inventory of numerous products and services. However, there is no data for the research phase of an emerging PV technology’s life cycle. For the researchers at the U of A this was an opportunity to collect information on the environmental impact of the research phase of an emerging PV technology where novel materials and device structures are continuously explored for delivering better solar cell efficiency. This student-advisor team undertook a study to address: “How energy efficient is renewable PV research?” Collaborating with Dr. Gregory Salamo’s research team, the energy demand for performing research on a sample of InGaAs quantum-wire based PV cell was quantified, as a demonstration test-bed. The research process consumed 930kWh of energy which is about the amount of energy consumed monthly by an average Arkansas household. The
test-bed system proved fruitful. Never before was the total energy demand quantified for a research-scale endeavor. Results clearly showed that the research community needs to be mindful of the energy, and especially non-renewable energy, used for research.

The energy hotspots in the research process of quantum-wire PV cells were the heating and cooling systems, in particular, the heating, ventilation, and air conditioning of facilities. This research would impact the academic community by helping scientists and engineers foresee energy consumption before setting up a new lab. Also, it was recommended that equipment not be kept idle for too long as there is a high energy overhead to keep systems standing by.

This research has been recognized at several poster competitions and is soon to pursue publication in one of the esteemed journals in the field of energy research and life cycle assessment. “Dr. Malshe’s vision has led us to do a long-pending analysis and introduced the elephant in the room,” says Ms. Mukherjee. “And we are grateful to Dr. Salamo for helping us by providing a test bed vehicle for this case study.” The researchers at the university expect that their study will prove useful not only to the academic community, but also to research units of small businesses, to investors, power suppliers, regulators, lobbyists, and policy makers. Our interview concluded with Ms. Mukherjee stressing that we must consciously conserve energy, even at the research-scale, “because kWh is the currency of the future.”
Appendix B: Executive summary of new knowledge created as part of the research

New knowledge found from this research include the results of the research and the primary (measured) data collected to create the life cycle inventory.
Appendix C: Potential patent and commercialization aspects

As there is no intellectual property, patents are not applicable.
Appendix D. Broader impact of research

D.1 Applicability of Research Methods to Other Problems

The research methods used for this case study are based on LCA methodology and LCA is a standard that can be used for any product or service. By that principle, this methodology can be applied to any product/service. Moreover, the model created specifically for the test-bed system for this case study can be applied to all emerging nano-material based PV technologies. The constraint would be the use of similar equipment or unit processes for the system. This includes use of MBE for material growth, photolithography for fabrication, and other processes as mentioned in the process flow (system diagram: Figure 15).

D.2 Impact of Research Results on U.S. And Global Society

This research would redefine the way we think about research. In the U.S., where a lot of energy is squandered, policies may be put in place to conserve more energy. While industries already conserve energy to minimize operating costs, the academic world will learn to adopt methods to be more conservative when it comes to research endeavors.

Overall, this project will help scientists worldwide bear in mind the energy impact of their research, especially if the research involves energy harvesting technologies. Designing more conservative approaches to performing research will help universities lower their indirect expenses. This will be good news for funding agencies as well.

D.3 Impact of Research Results on Environment

This research presents key industrial foresight to researchers who are pushing the boundaries of technology. Non-renewable energy sources are becoming scarce and scientists and engineers need to be aware of the energy demand of research. Progressive action toward energy
conservation based on the results of this research will lead photovoltaics into being considered more seriously as a potential candidate for utility scale alternative energy generation.
Appendix E. MS Project file

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<th>2014</th>
<th>2015</th>
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Appendix F: Identification of all software used in research and thesis generation

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| Serial number: JH7VBS1 |  
| Location: Nano 301 |  
| Owner: MicroEP, UA | Operating system: Microsoft Windows 7 Professional  
| Product ID: 00371-OEM-8992671-00524 |  
| Owner: MicroEP, UA |  
| Mendeley Desktop 1.11 | Owner: Shilpi Mukherjee  
| Microsoft Office Professional Plus 2010 | Owner: Shilpi Mukherjee through UA  
| Product ID: 02260-018-0000106-48850 |  

Appendix G: Publications planned

This research will be submitted to *Procedia Manufacturing*. 
Reference for Appendix

