Life Cycle Analysis of the AFRESH Home Photovoltaic System

By:

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Acceptance Note

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Abstract

Issues such as global warming, climate change and air quality have pushed our society to begin considering cleaner forms of energy generation. With green technologies such as photovoltaics becoming more popular, a question about their burden on the environment has risen. Do these systems have a net positive energy?

That was the question posed about British Columbia Institute of Technology's AFRESH Home. The AFRESH Home provides BCIT an opportunity to work in cooperation with industry partners in the development and demonstration of new housing and construction products and technologies. With all of its technologies installed to enhance energy efficiency and produce green energy, it is a net energy producer?

This study focuses on the photovoltaic energy system of the BCIT AFRESH Home. This includes a bank of building integrated photovoltaics, a bank of external roof-mounted photovoltaics, a GridPoint Connect Appliance for power management and storage, and the balance of the system including array supports cabling, and fasteners.

To answer this problem, a life cycle analysis was performed using system specific parameters including an inventory of the components and a regional specific weather data to determine the power generation. This involved evaluating four metrics: Cumulative Energy Demand (CED), Energy Payback Time (EPT), Electricity Production Efficiency (EPE), and Net Energy (NE).

After analyzing the data, it was found that the Energy Payback Time was 6.3-9 years with the PV module being accountable for 65 percent and batteries being responsible for 26 percent of that. The Electricity Production Efficiency was found to be a factor of about 3.3-4.8, stating that the AFRESH Home will payback its embodied energy 3.3-4.8 times throughout its operating life. The Cumulative Energy Demand was 177 GJ and The Net Energy was determined to be 234 GJ.

The results found were slightly less optimistic than general studies had shown in the research for this project. This was owing to several parameters of the specific environment that included the utility grid efficiency, the local solar irradiation and the low power density of the building integrated photovoltaics. When the standard parameters were assumed, the results of this study fell in line with the findings of many other published studies.

The AFRESH Home has already been generating energy for several years and is very near or past its Energy Payback Time. This value means that after that time all the energy produced is a surplus and the system is a net energy producer. This confirms the hypothesis that the AFRESH Home is a net energy producer.

Acknowledgements

This project would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

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1 Introduction

As part of its sustainability efforts, BCIT is working towards reducing its ecological footprint. To help accomplish this goal, BCIT has committed to an initiative to restructure a portion of the north end of the Burnaby Campus, coined the “Sustainability Precinct”. The goal is to create a Factor Four (75%) reduction in energy and materials consumption.

Playing a key role in this initiative is the AFRESH Home. AFRESH is an acronym standing for: Accessible & Affordable, Flexible, Resilient, Energy Efficient, Sustainable, and Healthy. The Home provides BCIT an opportunity to work in cooperation with industry partners in the development and demonstration of new housing and construction products and technologies. The AFRESH Home was designed with flexible mechanical and electrical systems making retrofits to integrate new technologies simpler. This allows the Home to continue to showcase the most current technological developments. One of these technologies is a photovoltaic system.

Figure 1: AFRESH Home at BCIT Burnaby Campus

Photovoltaics continue to be a rapidly growing sector of the energy market. Like all green technologies, locale and climate play largely into the energy generation of these systems. As photovoltaics continue to become more efficient and lower material requirements, they become more viable in less ideal conditions. Vancouver is an example of one of these locations being in a region labelled as a low irradiation climate (1100 $kWh/m^2/yr$).

1.1 Project Background

The BCIT AFRESH Home was originally named Home 2000. The Home started a collaborative project of BCIT School of Construction and the Environment, the CMHC, UBC School of Architecture, the Greater Vancouver Home Builders’ Association and the Canadian Plywood Association [1]. Home 2000 was showcased at the BC Home Show, and was then relocated to the BCIT Burnaby Campus where it still stands next to the J.W. Inglis Building (NW1) [2]. BCIT continues with projects in line with the Home’s original intent: to promote sustainable construction and energy generation within residential buildings.

When Home 2000 was constructed, a 2 kilowatt building integrated photovoltaic (BIPV) system was included [3]. Since this time, the (now) AFRESH Home has been retrofitted with several different technologies to test and promote. The modular design of the Home makes these retrofits simple compared to a traditional house. These retrofits included a geo-exchange system, a natural gas fuel cell, "smart" appliances, and further photovoltaic system upgrades.

1.2 Motivation

The current aspirations of the AFRESH Home are to become greenhouse gas neutral and to be energy independent. To achieve these goals, the AFRESH Home wants to not only generate its own electricity, but generate enough surpluses to account for the energy needed to manufacture, implement and eventually decommission the technologies on site; or in other words, recover the embodied energy of the system. To define the embodied energy for the system, the electricity generation systems must be looked at individually to allow for a thorough life cycle analysis (LCA). This LCA will help determine if the examined system is a net energy producer.

2 Framework and Methodology

The framework the ISO 14040:2006 [4] presents can be seen in Figure 2 below.

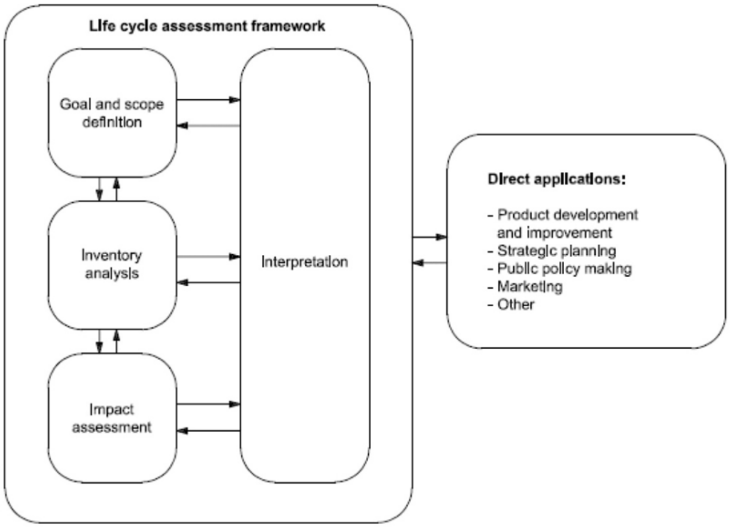

Figure 2: Stages of a Life Cycle Analysis [4]

The framework identifies four key components to the life cycle analysis. These are the goal and scope definition, the inventory analysis, the impact assessment, and the interpretation. The methodology for this project followed the guidelines as defined in ISO 14040:2006 [4] and ISO 14044:2006 [5] which lay out the necessary components for the goal and scope definition.

There are four life phases to be considered plus one auxiliary phase. The life phases are Raw Material Acquisition, Manufacturing, Usage, and Decommissioning. The auxiliary phase is Transportation. The energy in and out of these phases is shown in Figure 3.

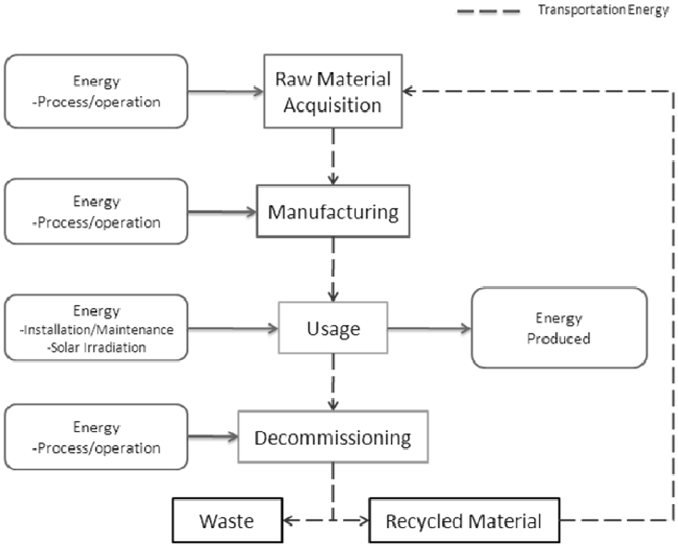

Figure 3: Energy Input/Output Block Diagram

3 Goal Definition

The intended application of this study was for the research of the British Columbia Institute of Technology Sustainable Development and Environmental Stewardship. The reason for the study was to test the hypothesis that the BCIT AFRESH Home project's photovoltaic system is a net energy producer when including the embodied energy of the system. The intended audience was the Faculty of B.Eng Dept and Sustainable Development and Environmental Stewardship. The results of this study were obtained to provide a basis for comparison between solar power generation systems and public grid power for the AFRESH Home.

4 Scope Definition

The scope is an integral part of a life cycle analysis. The scope gives a clear boundary to the system and allows the analysis to remain consistent throughout the entire undertaking.

4.1 System of Study

The system this project considers is the photovoltaic (PV) system. This includes the original BIPVs as well as the retrofit of frame-mounted roof PVs, the GridPoint Connect energy management system and the balance of the system (BOS). A block diagram of the system is shown below in Figure 4.

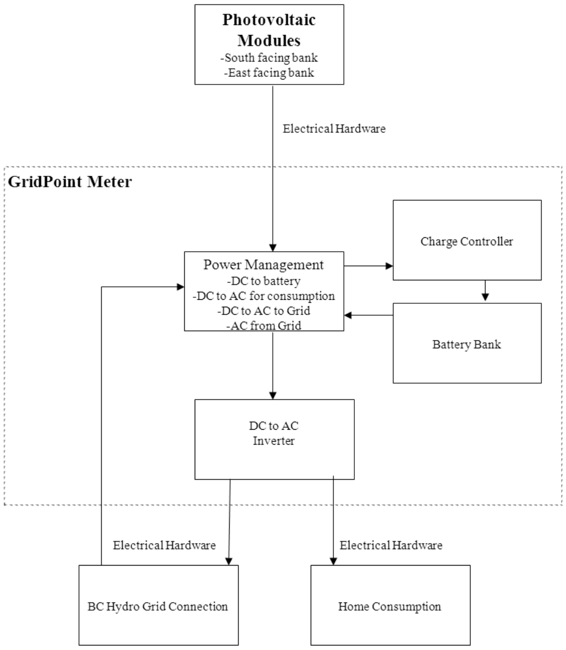

Figure 4: PV System Block Diagram

This block diagram is the simplified model that will be used for this project. The main components of focus are:

- Building integrated PVs
- Frame-mounted PVs
- GridPoint Connect Appliance (simplified)
- Balance of system (not pictured)

4.1.1 Building Integrated PVs

As mentioned earlier, the BIPVs are the original system installed on the Home. There are 18 frameless polycrystalline arrays (pc-Si) with a total of approximately 2kW [2; 3] or 110 watts per module. The specification sheet for these arrays was not available. The measured dimensions of the BIPV modules are 0.8m x 2.3m x 10mm. When the house was relocated to BCIT, it was positioned such that the BIPVs were facing east. The reasoning for this is unclear but it is suspected that that was the only way the building could fit in the available location.

4.1.2 Frame-Mounted PVs

There are six aluminum framed pc-Si PV modules (model # SF190-27-P190) facing south mounted at the front of the Home. See Appendix A for specification sheet. Each of these arrays is capable of producing 190 watts for a total of approximately 1200 watts. The dimensions of these modules are approximately 1m x 1.5m x 0.05m and a mass of 18kg. These were a retrofit installed in 2006 that involved mounting an array support frame to the existing roof structure and then attaching the arrays to the supports.

4.1.3 GridPoint Connect Appliance

The GridPoint Connect is an intelligent energy management system that integrates all the components of a renewable energy system into a cabinet smaller than a refrigerator. The internal components include eight 12V batteries, two charge controllers, one inverter and a PLC to control the unit. The model used in this installation is the GridPoint Connect C36-10-4.

This system also uses a logic algorithm to determine what to do with generated energy and how to power the connected system load (e.g. The Home). These decisions include whether to store the energy generated, convert and use it, or convert and send it to the public grid. The intent is to reduce the amount of power drawn from the public power grid (BC Hydro) and return power to the grid when not needed within the home.

4.1.4 Balance of System

The balance of the system (BOS) is defined as the array supports, cables and wiring, connectors and any other miscellaneous components. An average value was used for this as it is difficult to account for all the small pieces used in an installation. For further details, refer to Section 6.3.

4.2 Functional Unit

The functional unit used was the mega-joule per meter squared [MJ/m^2]. The embodied energy inputs into the PV modules are generally area dependent, not power rating dependent [6]. This allows for a comparison between the energy output of the module to the energy input throughout its life and for easy comparison to other modules of varying dimensions and efficiencies.

4.3 System Boundaries

The system boundary for this study was defined as follows. The analysis will begin from the manufacturing stage with established embodied energy values for raw materials as inputs. The analysis will end at the decommissioning stage of the life cycle. Any input or output that is either less than 5 percent of energy flow through a phase or 5 percent of the mass of the end product was omitted. Also, the manufacturing facility overhead and capital equipment was not considered nor was the energy to install the system. Please refer to Section 6 for further explanation.

4.4 Interpretation Methods

This study focuses on the net energy produced by the analyzed system as installed on the BCIT AFRESH Home. The Cumulative Energy Demand (CED), Energy Payback Time (EPT), Electricity Production Efficiency (EPE), and Net Energy (NE) will be calculated. The effects of emissions are not considered, though they can be correlated to the EPT, EPE, and NE metrics [6;

7]. Data will be gathered from reputable national databases. Only data that is found to be consistent will be used.

4.5 Limitations

This study is limited to the system as it is installed on the BCIT AFRESH Home in the climate of Vancouver, British Columbia, Canada; the location this project resides. Results may vary with other climate considerations, and this has been omitted from this study.

Another limitation for this study is that the system could not be dismantled to directly measure the mass or volume of materials used for each component nor was there access to the manufacturing facilities of the components. Because of this, data sheets of the components as well as established accounts of these values were used.

4.6 Assumptions

Energy generation data for the specific AFRESH system is available but not over a long enough span to accurately represent an annual average. Therefore an assumed value will be derived based on the system's capacity and on the statistical average annual weather patterns in Vancouver, British Columbia.

All raw materials will be evaluated as cradle-to-gate for LCA purposes. This means that all the required energy is accounted for up until it leaves the suppliers' facility "gates". Transportation of the raw materials to the manufacturers is assumed to be negligible. It is also assumed that there is no intermediate manufacturing transportation and that each component is manufactured in one facility. This is a fair assumption for the PVs as the manufacturer (SolarFun) states this on their website [8].

The performance ratio for the PV system is assumed to be 77%. This is a common value used that accounts for inefficiencies caused by the inverter, electrical line loss, snow, dust, and shade covering of the PV modules as well as heat (PV efficiency varies with temperature) and conversion losses [6; 9].

The grid efficiency was taken to be 0.35. This is the U.S. National grid average and is a standard used in many PV LCAs [6; 7; 10; 11]. Attempts were made to obtain a verified estimate for the BC Hydro grid but this was not available. However, it is generally assumed that the BC grid efficiency is higher (closer to 0.5) because the majority of the power is produced through hydroelectric turbines which have a greater efficiency than fossil fuel plants. This higher efficiency will yield different results for the energy metrics used. Others assumptions made were that the entire system was installed at the same time; all embodied energy invested for all phases is at present time and all components will span the same lifetime unless replacement is specified.

Other assumptions were made through other stages of the life cycle analysis and will be stated in the appropriate sections.

5 Impact Assessment

Several different impact assessments were implemented in this project. These indicators are known as metrics. These metrics are listed below:

1. Cumulative Energy Demand (CED)
2. Energy Payback Time (EPT)
3. Electricity Production Efficiency (EPE)
4. Net Energy (NE)

In the following sections, these metrics will be derived and explained.

5.1 Cumulative Energy Demand (CED)

The term Cumulative Energy Demand or CED is simple the total embodied energy of the system. This is often presented in the functional unit [MJ/m^2] but in this report it is presented in megajoules because the results are not meant for generalization and extrapolation to other systems.

$$\boldsymbol{CED = E_{material} + E_{manufacturing} + E_{use} + E_{end\ life} + E_{transportation}}\ [\mathbf{MJ}]$$

Where:

$$E_{material} = \sum_i (E_{material\ i} * m_{material\ i})$$

$$E_{manufacturing} = \sum_i (E_{process\ i})$$

$$E_{use} = E_{install} + E_{operation} + E_{maintenance}$$

$$E_{end\ life} = E_{dispose} + E_{recycle}$$

$$E_{transportation} = \sum_i (E_{transportation\ i})$$

It should be noted that this value is typically stated as positive value; it is the value invested into the system. Minimizing this metric will maximize overall system benefit. This means it is a measure that is independent of any lifespan or energy production assumptions, but not practical by itself as it would not be enough to draw any useful conclusions about the viability of a PV system.

5.2 Energy Payback Time (EPT)

Energy Payback Time (EPT) is generally presented in years for PV systems and represents the length of time it takes a system under specific operating conditions to recover the CED investment. At this point, the system is said to have a net zero energy balance.

$$EPT = \frac{CED}{YEO} * C\ [years]$$

C is the conversion efficiency of the utility grid (BC Hydro or other). This allows for compatibility of the CED which is calculated in terms of primary energy and the YEO or yearly energy output which is calculated in electrical energy with the following equation:

$$YEO = 3.6 * I_{solar} * A_{PV} * \varphi * PR\ \left[\frac{MJ}{year}\right]$$

Where:
3.6 is a conversion factor [MJ/kWh]
I_{solar} is the local solar irradiation in units of kWh/m^2/year
A_{PV} is the area of solar cells
φ is the PV conversion efficiency (0.15 in this project)
PR is the performance ratio (0.77 in this project)

This formula for YEO is valid for PV modules that are assumed to be in the optimum fixed axis configuration for their region. This is a widely used metric because it provided a meaningful estimate of time to see returns on invested energy. This method is similar to a Net Present Value (NPV) calculation in economics. While this metric does make assumptions and estimates of energy output, it does not require an estimated lifespan (assuming the EPT is relatively short). Minimizing this metric will maximize overall system benefit.

5.3 Electricity Production Efficiency (EPE)

Electricity Production Efficiency (EPE) is the dimensionless ratio of total energy output to energy input. This is equivalent to the ratio of total energy output to the CED.

$$\eta = \frac{E_{produced}}{CED} = \frac{YEO * t_{life}}{CED * C}$$

Where:
t_{life} is the lifespan in years
C is the utility grid conversion efficiency

This metric is dependent on the system life, whereas the CED and EPT are independent of the lifespan. This adds one more assumed variable which adds uncertainty to the result. It can be a useful comparison as long as an equal lifespan is considered. Maximizing this metric will maximize overall system benefit.

5.4 Net Energy (NE)

The net energy of the system is calculated as the total sum of all energy flows throughout the entire life of the system. This value is given in megajoules of electrical energy but can be given in megajoules of primary energy. This metric also assumes a lifespan and energy production over the entire life. These factors, as well as the actuality that the value is generally a large number that is not tangible to the average person, care should be given when using this metric. Maximizing this metric will maximize overall system benefit.

$$NE = YEO * t_{life} - CED * C \; [MJ]$$

Where:
t_{life} is the lifespan in years
C is the utility grid conversion efficiency
3.6 is a conversion factor [MJ/kWh]

6 Inventory Analysis

This section outlines the materials and processes considered for each system component and life section. It also will explain any omissions made owing to the system boundary.

6.1 Photovoltaic Modules

As mentioned in section 4.1, there are two separate solar arrays installed on the AFRESH home. Both PV modules are multi-crystalline silicon modules (mc-Si). There are three main differences in these panels:

1. Backing material
2. Module supports and frames
3. Replaced roofing area

Backing material - The materials used for the backing on these modules are different because of their intended use. The BIPVs were used to allow light through, like a sky light. Therefore, the backing plate was required to be transparent. Glass was used as the backing for these. The retrofitted PVs however were designed to be installed on an existing roof structure and therefore there is no requirement for backing transparency. The backing material used was sheet aluminum and a plastic coating. This allows for a lighter module.

Module supports and frames – Again, these PVs intended use has given them varying requirements for installation. The BIPVs are installed directly to the roofing structure in place of the traditional roof. There is therefore no additional burden of a supporting frame or a module frame. The retrofitted PVs require an aluminum frame to secure them to the existing roof structure and are also individually framed with an aluminum extrusion as seen in Figure 5 below. This extra material energy is considered in the retrofitted PV overall energy burden.

Figure 5: Array Support Frame for Retrofitted PVs

Replaced roofing area – As mentioned above, the BIPVs replace a portion of the traditional roof, as pictured below in Figure 6. This allows for less roofing materials to be used and is considered as a positive energy credit for this system. These materials include plywood, corrugated galvanized steel (roofing material of choice), and nails. The embodied energy of the roof paint was omitted as it was a small enough amount to warrant from the scope and boundaries for the project. The embodied energy of the insulation is not considered as it would generally be installed in this type of installation but the panels were left open for demonstration purposes. The retrofit does not reduce the needed roofing materials so it does not receive this energy credit.

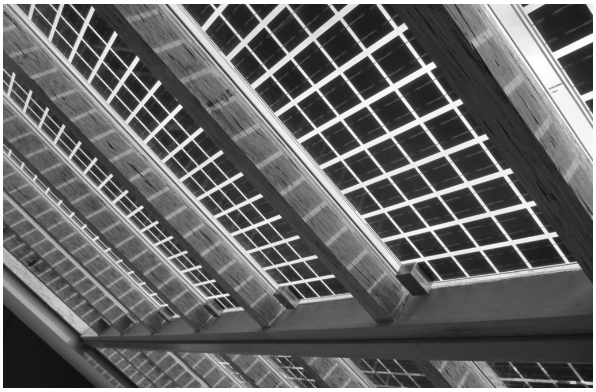

Figure 6: BIPVs in the AFRESH Home

The remaining materials and processes used to manufacture the PVs are common to both modules. These include silicon, glass, stainless steel (substrate), copper, Ethylene-vinyl acetate (EVA) laminates and adhesives. A typical PV layer scheme is shown in Figure 7.

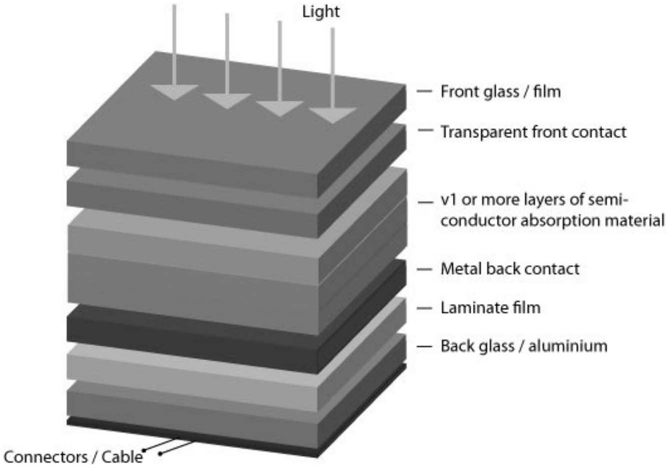

Figure 7: Layers of a Solar Module [12]

Some assumptions and approximations were made to account for the materials in a module. Calculations were carried out in Appendix D and the mass of each raw material was determined for one module and for 1m^2. These values as well as the raw material embodied energy values are tabulated in Table 1for the framed PVs and Table 2 for the BIPVs. It should be noted that the mass of the raw materials for the framed PV sums to 18kg which is the mass quoted for the framed PV off the specification sheet (Appendix A). While there were some material omissions, this sum accounts for them within a reasonable margin of error. Assumptions such as average weather patterns will have a larger affect on the error but are unavoidable.

Table 1: Raw Materials Inventory - Framed PV

Raw Material	Primary Energy [MJ/kg]	Mass [kg/unit]	Functional Unit [MJ/ m^2]
Aluminum	157	5.5	576.8
Silicon	2355	1.5	2396.8
Glass	18	7.5	89.9
stainless steel	46	2	61.2
copper	69	1.0	46.2
EVA film	52	0.5	17.3
	Total	**18**	**3188**

Table 2: Raw Materials Inventory – BIPV

Raw Material	Primary Energy [MJ/kg]	Mass [kg/unit]	Functional Unit [MJ/m2]
Silicon	2355	0.9	1103.1
Glass	18	14.9	142.9
stainless steel	46	2	48.6
copper	69	0.1	2.5
EVA film	52	0.5	13.7
Galvanized Steel	-29	18.4	-278.6
Nails - Steel	-29	0.12	-1.8
Plywood	-15	10.77	-86.0
	Total	**18**	**945**

The raw material embodied energy values in Table 1 and Table 2 above are from ICE V2.0 (Inventory of Carbon and Energy), University of Bath [13]. This is the most complete free database for raw materials. The material profile for each material used is available at http://www.bath.ac.uk/mech-eng/sert/embodied/.

The most notable of the raw material burdens are silicon and aluminum. Both of these materials are very energy intensive to produce. The silicon is a vital part of the photovoltaic as it is the material that actually absorbs the light and converts it to electrical current [12]. The mass for the silicon is set by the modules power output. About 8 grams of silicon is needed for every watt of power [12]. This amount is expected to decrease in the future with further advances in the manufacturing techniques leading to thinner wafers [6]. The aluminum serves two purposes: a framing material and a backing material for the framed PV. The BIPV is frameless and has glass backing. The glass has a significant lower embodied energy but the aluminum backing was most likely chosen for weight reduction of the framed PV.

The processes involved in the manufacturing of the PVs are extensive, but have a negligible embodied energy [11]. Following the guidelines laid out in the scope definition and system boundary the following processes were included in Table 3.

Table 3: Manufacturing Processes - Energy Consumed [6]

Manufacturing Process	**Primary Energy [MJ/m^2]**
Wafer Production	1000
Cell Processing	300
Module Encapsulation	200
Total	**1500**

The wafer production involves the casting of silicon ingots and then the sawing of these ingots into the “wafers” seen within a PV module. This process also accounts for the wasted silicon as a result of the sawing. The cell processing is the laminating of layers together and connecting the stainless steel substrate as well as other processes. The substrate carries the current to the PV outlet wires. The module encapsulation includes the processes and extra materials used to encapsulate the inner layers in the front and backing pieces.

During the commissioning and usage period of the PV modules’ life it is generally assumed that there is no energy input [6; 7; 11]. Some authors have cast a much wider system boundary such as Howard Odum in his book, “Environmental Accounting: Emergy and Environmental Decision Making” [14]. Odum suggested two methods for accounting for installation. These were through the metabolic rate of a human (tradesman) or by national fuel share per person (energy used to get to the site) [15]. These numbers are considered small, vague and generally introduce more uncertainty without actually having a noticeable effect on the results [14]. The other energy input during usage that is omitted is the actual solar energy [7; 11]. The rationale behind this is the solar energy is there anyways. The sun will shine in any given location with the same intensity and duration regardless of what is in place at that location. It is because of this it is not considered. Therefore, the scope definition of this project results in zero energy added during the usage stage of the modules’ life.

The end of life management for PVs is relatively uncertain[7; 11]. There are several options though not all are viable. Manual disassembly is one of these methods. Two other scenarios are generally considered: PVs will be disposed of in a landfill near the original installation (negligible energy) or the PVs could be shredded and mechanically separated to recover some materials. This is the method used for automobiles and other goods that need to be broken down to recycle. The method of shredding is used in this report. The energy required is still quite low at approximately 100 J/kg [11; 16] but is included for completeness. This converts into approximately 1.2 MJ/m^2.

As for the energy it takes to actually recover the material (recycle into a useable form), this energy is accounted for in the life cycle of the next product it will be used in. For example, the aluminum extrusion from the framed PV may be recycled and used to make soda cans. The energy taken to recycle the material; and the benefit of reduced raw material energy; will be used as the raw material energy input in that life cycle and is therefore omitted from this life-cycle to avoid accounting for it twice. This is a common method for handling the recycling of materials in life cycle analysis [13].

The retrofitted PVs were manufactured and shipped from China. There was not information available on the manufacturing location for the BIPVs so it was assumed to be the same. The PVs were assumed to have been shipped via a 3000 TEU (20 ft equivalent unit) container ship with a 15 MW engine. This was found to be a fairly standard ship for the trade route of China to Vancouver [17]. Based on this ship size and its average fuel consumption (approximately 3000 kg/hour) [18], and the shipping volume for the PVs the embodied energy from transportation was calculated to be approximately 140 MJ/m^2. See Appendix E for further calculations.

The embodied energy of the two different PV modules is tabulated in Table 4.

Table 4: Embodies Energy Inventory - PV modules

Phase	**Retrofitted PV [MJ/ m^2]**	**BIPV [MJ/ m^2]**
Raw Material	3188	945
Manufacturing	1500	1500
Commissioning	0	0
Decommissioning	1.2	1.2
Transport	140	140
Total	**4829**	**2586**

As would be expected, the retrofitted PVs have higher embodied energy content. This is owing to the approximately 2000 MJ less embodied energy from raw materials. The material difference is from the lack of aluminum in the BIPVs and the reduction of silicon. The silicon cells in the BIPVs have greater spacing between them to allow light to pass through the modules. This explains the reduction of silicon. The power output is proportional to the amount of silicon (as stated earlier, approximately 8g Si/watt), and so the looser packing factor of the BIPV modules results in the lower power output of approximately 110 watts.

The value of 4829 MJ/m^2 obtained for a framed module agrees well with other papers fond in research. E.A. Alsema, an often cited PV LCA expert, calculated 4600 MJ/m^2 for a framed module [6]. R. Laleman found a similar value of approximately 4500 MJ/m^2[10]. There is however a wide variation in the results procured by different authors. The values range from 2400 to 7600 MJ/m^2 [10; 19; 20].

The value of 2586 MJ/m^2 obtained for a frameless module is lower than the corresponding Alsema frameless value of 4200 MJ/m^2 [6]. The reason for this is the same as is explained above. The packing factor of the BIPVs was quite low, and is generally assumed in other papers to be maximized. If a maximized value for this is assumed, the frameless module would have the same silicon embodied energy per unit area. Also, not all frameless modules are building integrated, so general studies such as the one of comparison does not grant an energy credit for replaced building materials. If these two assumptions are adopted, the only remaining raw material data is the burden of the aluminum. The aluminum embodied energy is approximately 576 MJ/m^2, resulting in an idealized frameless module value of 4253 MJ/m^2. This closely agrees with the comparison value. The original value is kept for this paper however because this project is focused specifically of the AFRESH Home, not a general study as the other value is for. With that said, the original value does still fall within the window presented above (2400 to 7600 MJ/m^2).

6.2 GridPoint Connect Appliance

The functional unit for the GridPoint appliance is Mega Joules per unit [MJ/unit]. This is because the unit will be the same for most residential installations and is not dependent on the photovoltaic area. The functional unit of [MJ/m^2] could be derived using the maximum power input to the appliance but this would imply that the appliance could be downsized to match the PV output.

GridPoint Connect appliance is actually an integration of several system components as was shown in Figure 4. All of these components are housed in a cabinet for a plug and play style installation. Therefore the appliance has been broken down into several components. These include the batteries, inverter and charge controllers, and the cabinet and hardware (including the computing hardware). There are several auxiliary components such as meters and sensors that fell outside the scope and boundary of the project.

Figure 8: GridPoint Connect Model C36-10-4 [21]

Figure 8 above shows a typical GridPoint Connect unit. The lower door houses the batteries and the upper panel houses the user interface and internal breakers.

6.2.1 Batteries

As discussed earlier, there are eight 12V 150Ah batteries stored in the base of the cabinet. These are lead-acid type (PbA) batteries that weigh approximately 57 kg each and are 1800 Watt-Hours each.


Figure 9: GridPoint Appliance Batteries

The raw materials inventory can be derived from the MSDS sheets for the batteries which list all the materials and express them as percentages by volume or mass. The battery MSDS can be seen is available on the manufacturer's (Enersys) website [22]. The material inventory is shown below in Table 5.

Table 5: Raw Materials Inventory - Batteries

Raw Materials	Primary Energy [MJ/kg]	Mass Percentage	Primary Energy [MJ/kg]
Lead	45	25%	11.25
Lead oxides	13	35%	4.55
Polypropylene	93	10%	9.3
Sulphuric acid	0	10%	0
Water	0	16%	0
Glass	18	2%	0.36
Antimony (Calcium)	0	1%	0
		Total	**25.46**

The raw material embodied energy values in Table 5 above are from ICE V2.0 (Inventory of Carbon and Energy), University of Bath [13]. This is the most complete free database for raw materials. The material profile for each material used is available at http://www.bath.ac.uk/mech-eng/sert/embodied/.

In Table 5 there are several materials listed as "0" MJ/kg. These materials are generally considered as zero because they are naturally occurring and require minimal energy to harvest. The total embodied energy per kilogram is approximately 25.46 MJ/kg. This translates into approximately 1450 MJ per battery.

The manufacturing phase for the PbA batteries includes grid manufacturing, paste manufacturing, plate manufacturing, plastic moulding, and assembly[23]. The heaviest energy burden comes from the process of making the lead oxide paste. These processes have been previously derived at 9.2 MJ/kg [23] and 0.42 MJ/Watt-Hour [24; 25](13 MJ/kg). The latter was used as it refers explicitly to the mass which was the method chosen for this inventory.

The usage phase of the PbA batteries is assumed to be zero. There is no regular maintenance needed or replacement components during the usage. There is however a shorter usage period when compared to the rest of the system. A typical PbA battery has a maximum life of 12 - 15 years[24; 25]. Therefore this study assumes that all of the batteries will be replaced once within the system lifetime, totalling 16 batteries used instead of 8.

As for the decommissioning phase, PbA batteries are up to 95% recyclable [23]. Since the batteries are assumed to be made of recycled materials, the energy burden of recycling is assigned in this life cycle. J.L. Sullivan and L. Gaines calculated the required energy to recycle PbA batteries as 17.1 MJ/kg [13]. Other studies have accomplished similar results [24; 25].

The transportation phase for the batteries is assumed to be from the Mexico manufacturing plant to the GridPoint assembly facility in Montreal, Quebec and then from there to Vancouver, British Columbia. The batteries are considered separate in shipping then the GridPoint appliance because of the extra set of batteries required for shipping. The second set of batteries is assumed to be ordered through GridPoint and therefore follow the same shipping route. The value used for this calculation is 0.72 MJ/ton km [25].

The total embodied energy inventory for the batteries is listed below in Table 6.

Table 6: Embodied Energy Inventory - Batteries

Phase	Primary Energy per mass [MJ/kg]	Primary Energy per unit [MJ/unit]
Raw Materials - Recycled	25.46	1451.22
Manufacturing	9.2	524.4
Usage	0	0
Decommissioning	17.1	974.7
Transport	6.3	359.1
Total	**58**	**3309**

The total embodied energy per battery totals 3309 MJ. Factoring in the 16 batteries used over the lifespan, the total embodied energy from the batteries is approximately 43 Giga Joules.

6.2.2 Inverter and Charge Controllers

The inverter and charge controller were expected to account for less than 5% of the total embodied energy and therefore were ruled out by the scope and boundaries for a thorough analysis. But to ensure consistency they were accounted for using a standard functional value. This is a commonly used method in PV LCAs.

Inverters are relatively simple devices and their physical size and weight (and therefore material content) is directly proportional to the capable load [26]. Because of this, the functional value used for inverters and charge controllers is 1 MJ/watt [6; 7]. From the GridPoint Connect Installation Guide, the inverter in the appliance is rated for 3.6kVA (3600 W) [27]. This results in a value of 3600 MJ of embodied energy for the inverter and charge controller. The assumption that this value is less than 5% of the embodied energy is correct.

6.2.3 Cabinet and Hardware

This section basically covers the remainder of the appliance. This includes the cabinet, the power management hardware and any fasteners and trim. Since the appliance could not be disassembled, data was taken from the installation guide to approximate the weight of the appliance and assumptions were made on the percent mass from different materials. The mass of the appliance without batteries was 148 kg [27]. It was assumed that the inverter and charge controller weighed about 3 kg and this was deducted as to not count this mass twice. Therefore a mass of 145 kg was assumed for this component group.

The raw materials assumed for this portion can be seen in Table 7.

Table 7: Raw Materials Inventory - Cabinet and Hardware

Raw Material	Primary Energy per mass [MJ/kg]	mass per module [kg/unit]	Primary Energy per module [MJ/unit]
Mild Steel	29	142.5	4184
Silicon	2355	0.5	1178
Copper	69	2.0	138
	Total	**145**	**5499**

As noticed in Table 7, the majority of the weight is assumed to be in steel. This unit is a large steel case with a heavy steel frame and rack for the battery banks. The silicon accounts for circuitry in the power management hardware and the copper accounts for the cables and wiring for the cabinet and batteries.

The manufacturing phase for this is assumed minimal. The processes required for the cabinet are low power consumption operations such as sheet metal cutting and bending. The processes for the circuitry are mostly accounted for in the silicon raw material energy, as from the raw material definition.

The usage phase of the appliance life is considered in this section only. The power management controller requires power to monitor the power and run its programs. The appliance runs on 120V and 60 W [27]. This works out to approximately 525 kWh per year (1.89 MJ/year). Following a 30 year assumed life, the calculated embodied energy is 57 MJ to power the system through its life.

The energy used to recycle and recover any materials is accounted for in the life cycle of the next product it will be used in. Therefore it was omitted from this life-cycle to avoid accounting for it twice. This is a common method for handling the recycling of materials in life cycle analysis [13].

The transportation phase of the GridPoint Connect appliance is based on the following assumptions: The components used within the cabinet were sourced local to the assembly facility in Montreal, QC and the appliance was shipped via semi-truck to directly to Vancouver, BC. The value used for this calculation is 0.72 MJ/ton km [25]. The distance is approximately 4550 km, and provided an embodied energy value of 475 MJ.

The total embodied energy inventory for the batteries is listed below in

Table 8: Embodied Energy Inventory - Cabinet and Hardware

Phase	Primary Energy per unit [MJ/unit]
Raw Materials	5499
Manufacturing	0
Usage	57
Decommissioning	0
Transport	475
Total	**6031**

The total embodied energy for the GridPoint appliance without batteries is 6031 MJ. With the batteries (including replacements) the embodied energy totals 9340 MJ.

6.3 Balance of System

The BOS was expected to account for less than 5% of the total embodied energy and therefore were ruled out by the scope and boundaries for a thorough analysis. But to ensure consistency they were accounted for using a standard functional value. This is a commonly used method in PV LCAs.

The BOS includes the array supports (for the retrofitted PVs), the cables, connectors, and fasteners used in the installation. The fasteners used in the installation for the BIPVs have already been accounted for in the energy credit of the roof replacement (see section 6.1). The cables for the two PV banks are assumed to be connected near the installation point; therefore a functional value for the BOS of a framed PV system can be used. The typical functional value used is 700 MJ/m^2 [20]. Using the area of the retrofitted PVs; for the reasons stated above; a value of 6273 MJ of embodied energy was obtained. The assumption that this value is less than 5% of the embodied energy is correct.

6.4 Total System Input

Taking the data from the previous section, it can be compiled to determine a total embodied energy value for the whole system over its entire lifespan, as specified in the scope definition. This data is tabulated in Table 9.

Table 9: Embodied Energy Inventory - Total PV System

Component	Raw Materials [MJ]	Manufacturing [MJ]	Usage [MJ]	Decommissioning [MJ]	Transport [MJ]	Total [MJ]	[%]
BIPV	31940	40325	0	32	140	72438	41%
Retrofit PV	28569	13442	0	11	140	42161	24%
Cabinet/Hardware	5499	0	57	0	475	6031	3%
Battery Bank	12960	12096	0	15504	5746	46306	26%
Inverter/Controller	n/a	n/a	n/a	n/a	n/a	3600	2%
BOS	n/a	n/a	n/a	n/a	n/a	6273	4%
					6501	**176808**	**100%**

Table 9 above shows the total embodied energy of the system as approximately 177 Gigajoules. The right column indicates the energy burden per component in percent. The PV modules combined account for 65% of the energy burden, and the batteries are responsible for 26 percent.

6.5 Total System Output

The total system output is approximated by using statistical data for the 30 year average of the weather and solar irradiation in Vancouver, BC. The solar irradiation is the irradiative energy the earth receives from the sun. Vancouver is considered an area of low solar irradiation, which means there is less available energy for the PV modules to absorb. Vancouver receives approximately 1100 kWh/m^2/year [28]. Areas of high solar irradiation such as California can receive approximately 1900 kWh/m^2/year [29]. This affects the Energy Payback Time, Electricity Production Efficiency, and Net Energy but does not affect the Cumulative Energy Demand for the same system. In section 5.2, the Yearly Energy Output (YEO) was introduced.

$$YEO = 3.6 * I_{solar} * A_{PV} * \varphi * PR \left[\frac{MJ}{year}\right]$$

Where:
3.6 is a conversion factor [MJ/kWh]
I_{solar} is the local solar irradiation in units of kWh/m^2/year
A_{PV} is the area of solar cells
φ is the PV conversion efficiency
PR is the performance ratio (0.77 in this project)

This is an approximation that makes several assumptions. A constant performance ratio and efficiency is assumed and the formula uses an annual solar irradiation. The PV modules' efficiency is temperature dependent and the performance ratio and solar irradiation is seasonally dependent. The performance ratio is generally higher in the summer, since there is virtually no coverage from snow, fallen leaves or frost. At the same time, solar irradiation is highest in the summer, meaning more available energy, but more heat losses (reduction of efficiency). To account for these variations, the National Renewable Energy Laboratory (NREL) developed a program called PVWatts (www.nrel.gov/rredc/pvwatts/). PVWatts performs an hour-by-hour calculation with corrections for things such as the PV module temperature's impact on PV efficiency, reflection losses, and inverter efficiency as a function of load, in addition to the DC-to-AC derate factors [30]. The program uses regional specific weather data from the following bodies for the calculations:

- Solar and Wind Energy Resource Assessment Programme (SEWERA)
- International Weather for Energy Calculations (IWEC)
- Canadian Weather for Energy Calculations (CWEC)

PVWatts intakes several parameters: system DC rating, derate factor (performance factor), array tracking, array angle, azimuth angle (compass direction) and regional energy cost.

This program was used to determine the YEO and the results were validated with hand calculations. Three scenarios were considered for calculation.

1. BIPVs current configuration: East facing
2. BIPVs ideal configuration: South facing
3. Retrofitted PVs current configuration: South facing

It should be noted that in scenario 2, there would be no roof area left for the retrofitted PVs to face south; this scenario was only considered to test the maximum possible output for the BIPV system when compared to the less ideal configuration of east facing. For the full PVWatts results please refer to Appendix B. For the YEO hand calculations please refer to Appendix C. The final results are presented below in Table 10.

Table 10: System Energy Production per Annum Based on Vancouver, BC

Scenario	PV Bank	Direction	Azimuth Angle [Degrees]	YEO [MJ/year]	YEO [kWh/year]
1	BIPV	East	30°	5584	1551
2[1]	BIPV	South	30°	7276	2021
3	Retrofitted PV	South	49°	4266	1185
1 and 3	-	-	-	9850	2736

Table 10 shows the three scenarios introduced above and the real world scenario of both PV banks together as one system. The total system produces an annual output of 2736 kWh or 9850 MJ. The average household consumption in British Columbia is approximately 11,000 kWh per year [31]. The AFRESH Home however would most likely have a lower consumption as it was designed with maximizing energy efficiency. Using the assumed 30 year system life results in a total system output of approximately 296 gigajoules was found.

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[1] As mentioned in section 4.1.1 the BIPVs on the AFRESH Home are positioned east even though the optimal configuration in the northern hemisphere is south. This concession results in an annual output reduction of approximately 23 percent.

7 Interpretation

With the completed life cycle inventory analysis, the data was interpreted using the energy metrics proposed in the impact assessment (section 5).

7.1 Cumulative Energy Demand (CED)

The cumulative energy demand for the system is by definition the total system energy input. This was calculated and presented in Table 9. The result was a system specific CED of 176,808 megajoules. The cumulative energy demand can be shown by component burden and this is graphically represented in Figure 10.

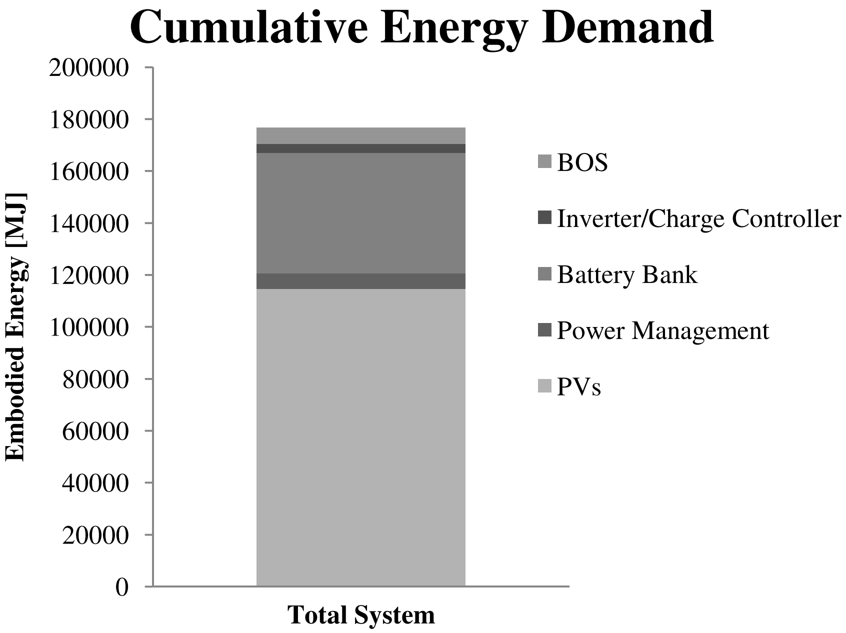

Figure 10: Cumulative Energy Demand Breakdown

The PV modules are shown together in Figure 10 and this accounts for the largest portion of the energy burden (65 percent). The battery bank is responsible for 26 percent of the energy burden, including the replacement of the batteries once in a lifetime.

7.2 Energy Payback Time (EPT)

The Energy Payback Time was calculated for the AFRESH Home based on the CED, YEO and the utility grid efficiency. The U.S. National grid efficiency (0.35) was considered for several reasons. The first is that is offers a better basis for comparison to other studies since this is a standard assumption in PV LCAs [6; 7; 10; 11]. The second reason is that an accurate and verified value for the BC Hydro Utility energy conversion efficiency was not available by the time of completion of this project. This report does however assumes an auxiliary estimated value for the BC Hydro Utility of 0.50 which is typical of smaller water turbine generation [32]. This estimate is based on the percentage of hydroelectric power generation in BC [31], which is more efficient than the popular thermo power generation within the United States [33].

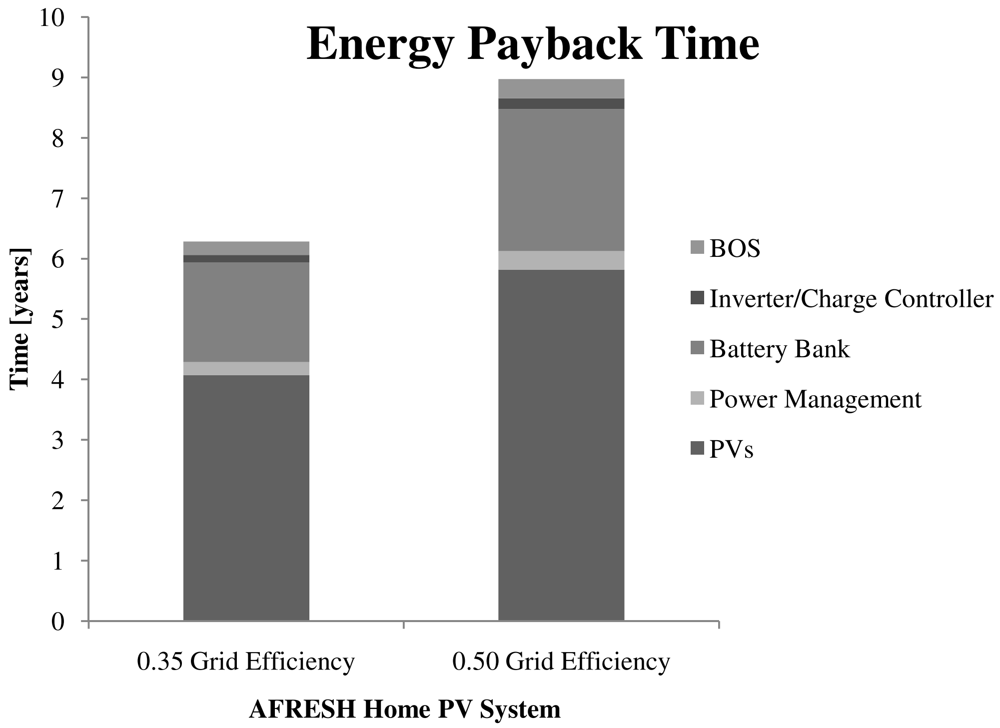

Figure 11: Energy Payback Time of the BCIT AFRESH Home PV System

Figure 11 above shows the two grid efficiencies and the effect on the EPT. The EPT for a grid efficiency of 0.35 is 6.3 years while the EPT for the grid efficiency of 0.50 is 9.0 years. The EPT for the PV modules only is approximately 4 years. Results obtained by Alsema agree with the PV module EPT of approximately 4 years in an area of low solar irradiation [6] and falls within the range of compiled values from C. Bankier that considered various solar irradiation levels [14].

7.3 Electricity Production Efficiency (EPE)

The Electricity Production Efficiency for the AFRESH system was calculated to be approximately 4.8 assuming a 0.35 utility grid efficiency and 3.3 assuming a 0.50 grid efficiency. Figure 12 below shows the cumulative energy balance at end of each year.

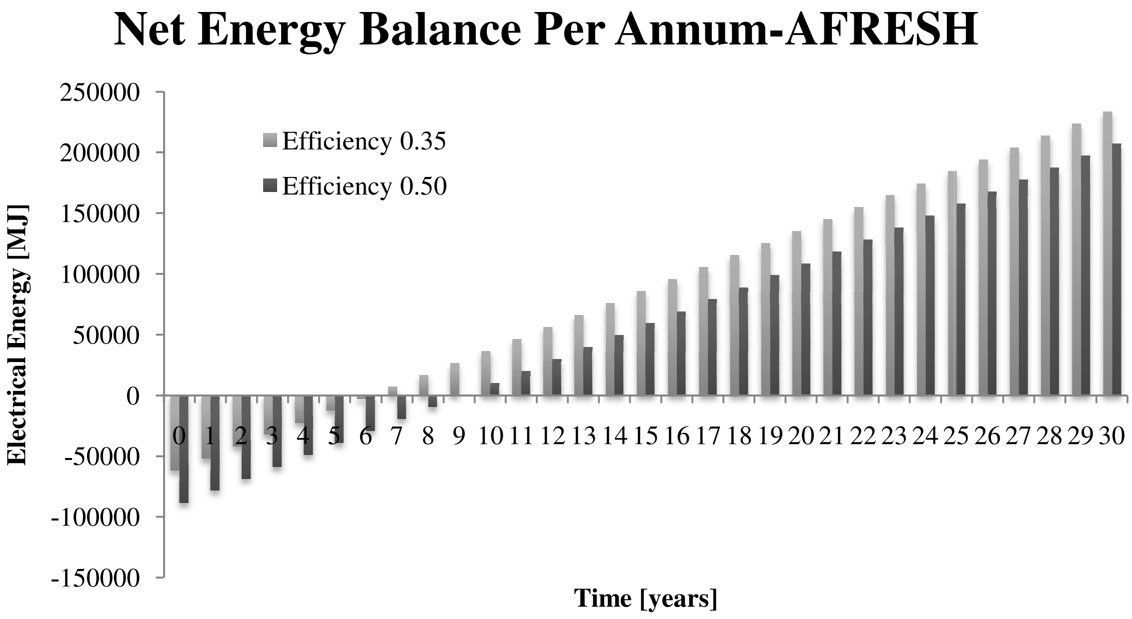

Figure 12: Net Energy Balance per Annum – AFRESH

The EPE can be seen visually in Figure 12 as the ratio of the magnitudes of the column in year 0 (left) and the column in year 30 (right). It can be seen how the lifespan would affect this calculation if year 0 is compared to year 20 or 25. Again, when using this metric, care must be given to ensure the lifespan assumed is equivalent.

7.4 Net Energy (NE)

The net energy is the final energy balance of the system after all energy flows have been accounted for. Within the scope of this project, this results in the cumulative value at the end of year 30. This metric can be seen illustrated in Figure 12. The NE value for the AFRESH Home is approximately 234 GJ of electricity assuming 0.35 utility grid efficiency and 207 GJ assuming a 0.50 grid efficiency.

With the 0.35 and 0.50 efficiency the system Net Energy in kWh is 64,890 kWh and 57,523 kWh respectively. When compared to that average annual household consumption of 11,000 kWh per year, this system produces enough Net Energy to power an average household for 5.9 to 5.2 years respectively.

7.5 Monetary Value of Energy Produced

The Economic Payback Time was not considered as a metric for this study. It was omitted because exact component costs were either not available or difficult to account for as many components were donated to the AFRESH Home. However the monetary value of produced energy was determined. The cumulative life value was also calculated following a simple payback model (straight-line) where the time value of money was not included, the utility price remained constant throughout the lifespan and all system costs were considered zero. The results are summarized in Figure 11.

Table 11: Energy Production Economic Value

PV Bank	YEO [kWh/year]	Utility Cost [$/kWh]	Produced Annual Value	Produced Life Value
BIPV	1551	0.0862	$ 133.70	$ 4,010.89
Retrofitted PV	1185	0.0862	$ 102.15	$ 3,064.41
Both	2736	0.0862	$ 235.84	$ 7,075.30

Table 11 shows an annual monetary value is $235.84. Based on the assumed average household consumption of 11000 kWh per year (annual cost of $948.20) the produced value results in a 25% reduction in energy costs. The full life monetary value is $7075.30. While the Economic Payback Time was not considered, average system costs are approximately 7-10 dollars per installed watt [34]. At these rates, the systems would not recoup the system costs. This is a common complaint with PV systems and because of this there are many government incentive plans available for green energy initiatives.

8 Recommendations

During the undertaking of the study, several opportunities for improvements become noticeable. The first recommendation is to consider a different type of battery when the GridPoint Connect batteries reach the end of their useful life. The lead acid batteries used have been found to have one of the highest embodied energy value per kg [24; 25]. The lowest embodied energy per kg for current battery technology suitable for this application is zinc bromide (Zn-Br) cells. Another solution to this is to monitor the cycling of the batteries and determine the necessity of batteries in this system. Batteries are useful for backup power in emergencies but the energy being created by the Home is generally not in excess of the Home load, meaning it is used immediately on site. If excess is produced as it has been found to do several times a year, the power can be returned to the grid. By considering the battery choice or elimination, the Cumulative Energy Demand can be lowered by up to 13 percent (half of the batteries' total embodied energy).

The second recommendation is to consider insulating the AFRESH Home Roof photovoltaics. Currently, as seen in Figure 6, the BIPVs are exposed to the interior of the attic. Temperature fluctuations can be great in this space. The space is not actively cooled and has a heat recovery system that re-circulates the heated air through the HVAC system. Therefore this does not cause an issue in the summer, but in the winter the lack of insulation would cause excessive heat loss that would have to be made up for by the HVAC system, increasing the energy burden. This was not accounted for in the LCA as it was stated that the BIPVs were left intentionally exposed for demonstration purposes, and would have been insulated in practice. A comprise could be made by insulating most of the BIPVs and only leaving 1 or 2 exposed for demonstration.

There are several recommendations for future work on this study. The first recommendation is to continue monitor the energy production and consumption through the GridPoint appliance. The second recommendation is to apply this data to the metrics used in this study to verify the results found within this study. The third recommendation is to undertake similar life cycle studies for energy saving systems within the AFRESH Home such as the geo-exchange system, and for the recently commissioned energy generating fuel cell. If studies of these systems offer similarly positive results as the study, the AFRESH Home may be able to quantify their goal of being energy independent and a net energy producer.

9 Lessons Learned

During the undertaking of this project, obstacles were realized along the way. These obstacles taught valuable lessons to consider in future projects of this nature. The first of these was the system boundary required for the life cycle analysis. The LCA system boundary needs to be firmly defined before starting to avoid a creeping boundary. This is a common issue in LCAs because the further back the components and materials are traced back, the more inclusions, and generally uncertainty, are included into the boundary.

Another valuable lesson in this project was in the comparison of different LCAs. LCAs can be a useful tool but care must be given to ensure LCAs are compatible before comparing. Differences in scope, boundaries, components, location, lifespan and many other variables take part in the results achieved from each photovoltaic LCA study. While many of these variables now follow assumed standards, not all authors use the same values and this can have large affects on the obtained results. One of the largest discrepancies in this study for comparison purposes was the utility grid efficiency. Because of this, both the standard assumption 0.35 and the project specific assumption of 0.5 were included.

Project management played a large role in the successful completion of this project. Organization of project tasks and the timeline governing them need to be sensitive to other commitments undertaken. Scheduling conflicts should not be underestimated as they will sum to create greater delays.

In a research based study such as this, it is important to practice good archiving of research. With dozens of research papers, industry journals, and web research; organization of these resources is important to allow efficient researching and ensure proper citation. To handle this archiving task, Bibus open source software was used.

10 Conclusion

In this study, the hypothesis that the AFRESH Home photovoltaic system is a net energy producer was investigated. This was done with the use of an ISO life cycle analysis. This considered several metrics to interpret the results. These metrics were Cumulative Energy Demand (CED), Energy Payback Time (EPT), Electricity Production Efficiency (EPE), and Net Energy (NE).

After analyzing the data, it was found that the Energy Payback Time was 6.3-9years. This value means that after that time all the energy produced is a surplus and the system is a net energy producer. The AFRESH Home has already been generating energy for several years and is very near or past its Energy Payback Time. The Electricity Production Efficiency was found to be about 3.3-4.8, stating that the AFRESH Home will payback its embodied energy 3.3-4.8 times throughout its operating life. This confirms the hypothesis that the AFRESH Home is a net energy producer.

The Net Energy and Cumulative Energy Demand are not as illustrative on their own. They are useful when paired with the other metrics involved but do not provide enough insight on their own. The CED does not consider how long it takes to payback the energy. A system with a high CED may produce more energy and actually payback the energy faster. Normalizing this metric into a per-square-meter metric can help with comparisons however. The Net Energy suffers from a similar deficiency. This value gives you a final output but does not lend itself to analysis of whether or not this is a reasonable return on the investment. However these metrics can be useful as supplements to the EPT and the EPE. The Net Energy was determined to be 234 GJ and the Cumulative Energy Demand was 177 GJ with the PV module accounting for 65 percent of the EPT and the batteries being responsible for 26 percent of that. The Cumulative Energy Demand can be minimized by using frameless modules and building integrated modules, saving the embodied energy of the aluminum.

This study has shown that solar energy generation is viable in a low irradiation climate (1100 kWh/m^2/yr) in terms of the studied metrics. The AFRESH system was determined to produce an approximate annual output of 2736 kWh or 9850 MJ. This system results in a 25 percent reduction in energy consumption when compared to the average household consumption in British Columbia is approximately 11,000 kWh per year.

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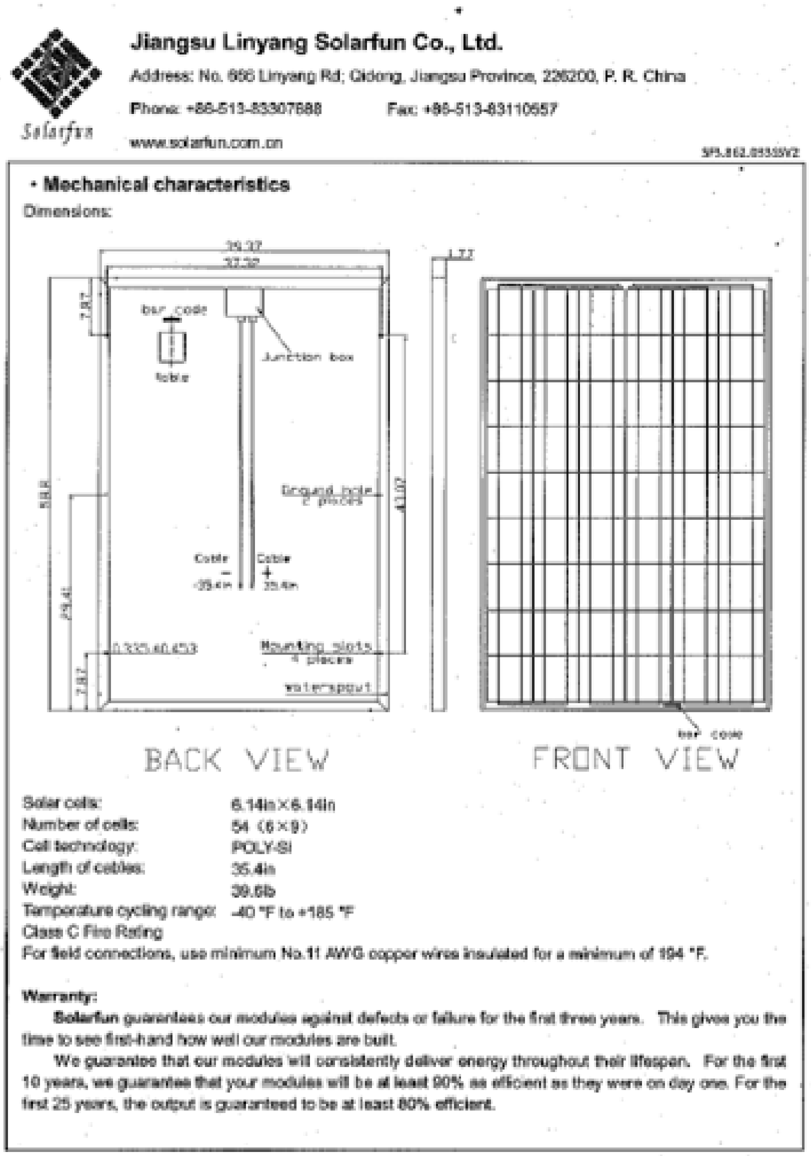
Appendix A - PV Module Specification Sheet (SF 190-27-P)



Jiangsu Linyang Solarfun Co., Ltd.

Address: No. 666 Linyang Rd; Qidong, Jiangsu Province, 226200, P. R. China
Phone: +86-513-83307688 Fax: +86-513-83110657
www.solarfun.com.cn

SFS.862.0555V2

· Mechanical characteristics

Dimensions:

Solar cells:	6.14in×6.14in
Number of cells:	54 (6×9)
Cell technology:	POLY-SI
Length of cables:	35.4in
Weight:	39.6lb
Temperature cycling range:	-40 °F to +185 °F

Class C Fire Rating

For field connections, use minimum No.11 AWG copper wires insulated for a minimum of 194 °F.

Warranty:

Solarfun guarantees our modules against defects or failure for the first three years. This gives you the time to see first-hand how well our modules are built.

We guarantee that our modules will consistently deliver energy throughout their lifespan. For the first 10 years, we guarantee that your modules will be at least 90% as efficient as they were on day one. For the first 25 years, the output is guaranteed to be at least 80% efficient.

Jiangsu Linyang Solarfun Co., Ltd.
Address: No. 666 Linyang Rd; Qidong, Jiangsu Province, 226200, P. R. China
Phone: +86-513-83307688 Fax: +86-513-83110557
www.solarfun.com.cn

SF3.862.6335V2

SF190-27-P PV Module Characteristics

• Electrical Characteristics

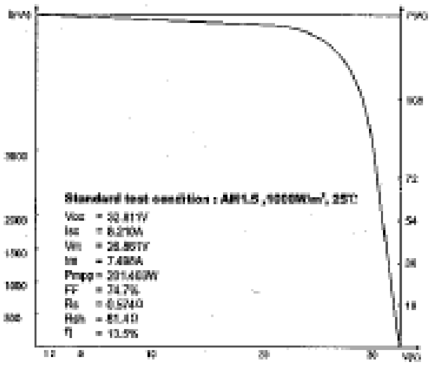
Module	Voc(V)	Isc(A)	Vmp(V)	Imp(A)	Pmax(W)
SF190-27-P170	32.2	7.54	26.3	6.47	170
SF190-27-P175	32.3	7.64	26.4	6.63	175
SF190-27-P180	32.4	7.72	26.5	6.80	180
SF190-27-P185	32.5	7.80	26.6	6.96	185
SF190-27-P190	32.6	7.98	26.7	7.12	190
SF190-27-P195	32.7	8.06	26.8	7.28	195
SF190-27-P200	32.8	8.24	26.9	7.44	200
SF190-27-P205	32.9	8.35	27.0	7.60	205
SF190-27-P210	33.0	8.48	27.1	7.75	210

All electrical specifications are +/-5%

All technical data at Standard Test Condition(STC): Irradiance level 92.9W/ft² spectrum AM1.5 and cell temperature 77° F

Maximum System Voltage:	600 V
Temperature coefficients of voltage:	-0.21%/°F
Temperature coefficients of current:	+0.02%/°F
Temperature coefficients of power:	-0.22%/°F
Nominal Operating Cell Temperature (NOCT):	113°F±6 °F
Maximum series fuse rating:	15A

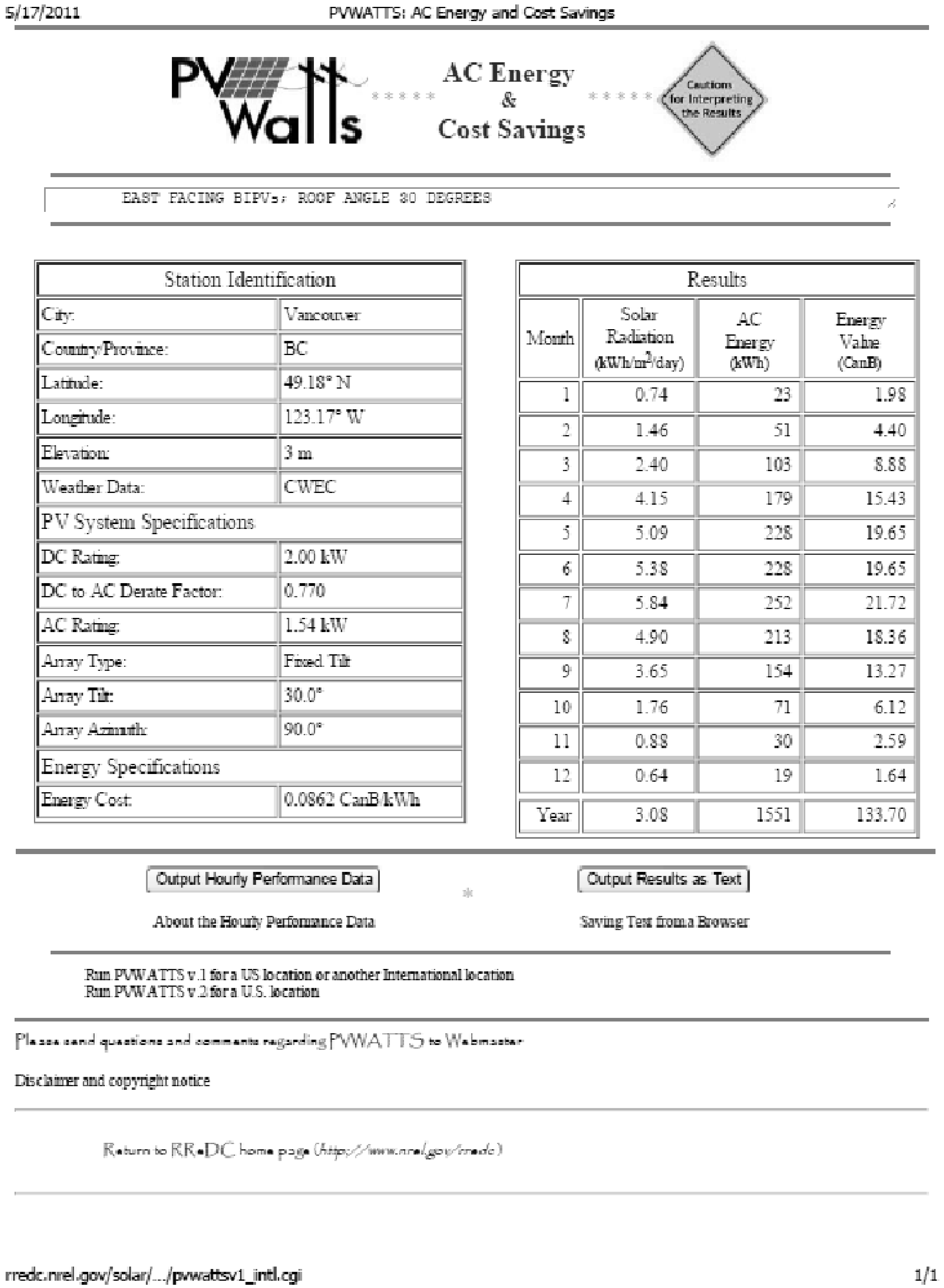
• I-V characteristic curve of a sample module



Appendix B - PV Watts Data and Results

C-1: East Facing BIPVs – As Installed
C-2: South Facing BIPVs – Ideal Situation
C-3: South Facing Retrofitted PVs – As Installed

C-1: East Facing BIPVs – As Installed



5/17/2011 PVWATTS: AC Energy and Cost Savings

EAST FACING BIPVs; ROOF ANGLE 30 DEGREES

Station Identification	
City:	Vancouver
Country/Province:	BC
Latitude:	49.18° N
Longitude:	123.17° W
Elevation:	3 m
Weather Data:	CWEC
PV System Specifications	
DC Rating:	2.00 kW
DC to AC Derate Factor:	0.770
AC Rating:	1.54 kW
Array Type:	Fixed Tilt
Array Tilt:	30.0°
Array Azimuth:	90.0°
Energy Specifications	
Energy Cost:	0.0862 CanB/kWh

Results

Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value (CanB)
1	0.74	23	1.98
2	1.46	51	4.40
3	2.40	103	8.88
4	4.15	179	15.43
5	5.09	228	19.65
6	5.38	228	19.65
7	5.84	252	21.72
8	4.90	213	18.36
9	3.65	154	13.27
10	1.76	71	6.12
11	0.88	30	2.59
12	0.64	19	1.64
Year	3.08	1551	133.70

About the Hourly Performance Data

Saving Text from a Browser

Run PVWATTS v.1 for a US location or another International location
Run PVWATTS v.2 for a U.S. location

Please send questions and comments regarding PVWATTS to Webmaster

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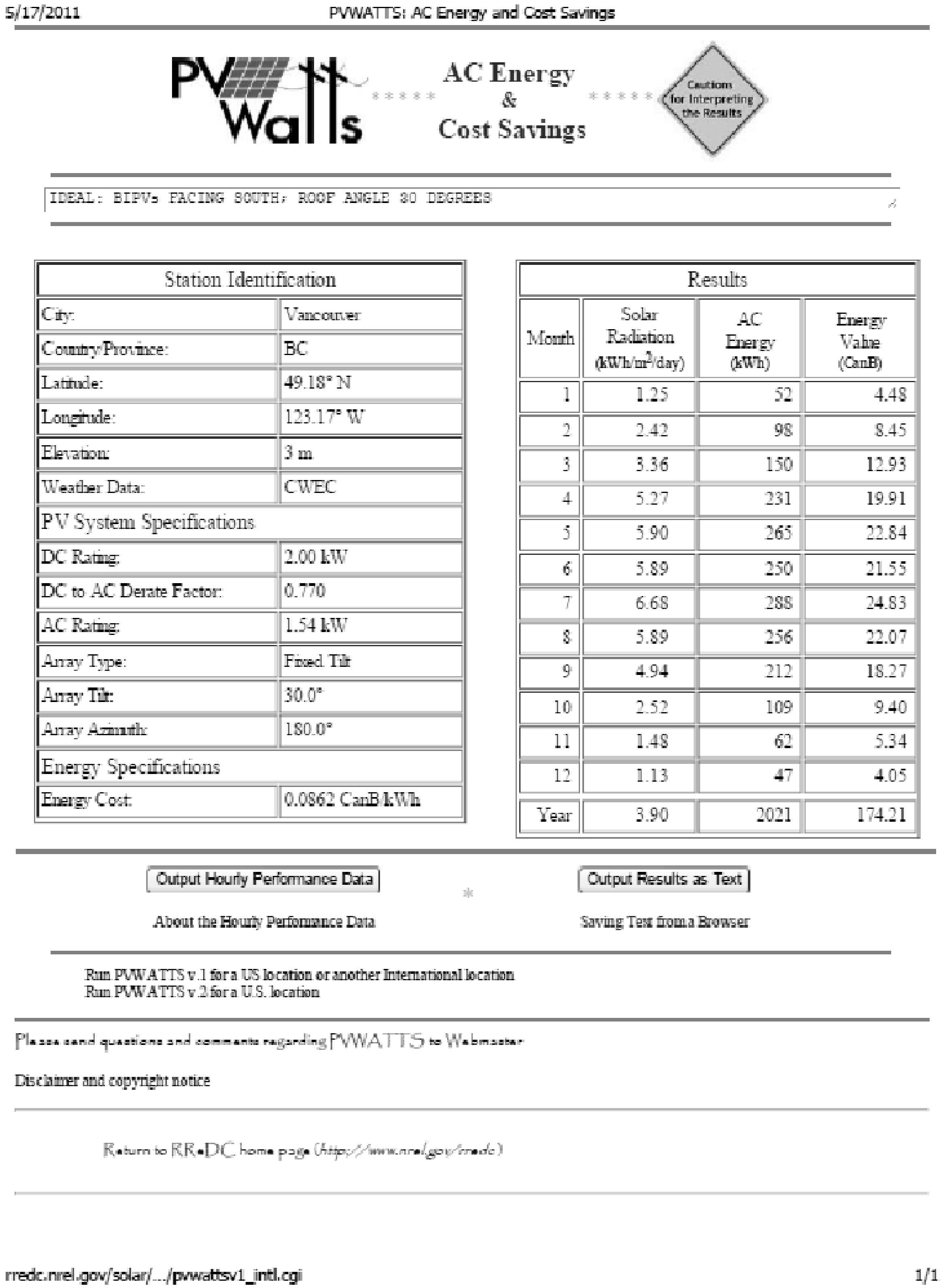
Return to RReDC home page (http://www.nrel.gov/rredc)

rredc.nrel.gov/solar/.../pvwattsv1_intl.cgi 1/1

C-2: South Facing BIPVs – Ideal Situation



5/17/2011 PVWATTS: AC Energy and Cost Savings

IDEAL: BIPVs FACING SOUTH; ROOF ANGLE 30 DEGREES

Station Identification	
City:	Vancouver
Country/Province:	BC
Latitude:	49.18° N
Longitude:	123.17° W
Elevation:	3 m
Weather Data:	CWEC
PV System Specifications	
DC Rating:	2.00 kW
DC to AC Derate Factor:	0.770
AC Rating:	1.54 kW
Array Type:	Fixed Tilt
Array Tilt:	30.0°
Array Azimuth:	180.0°
Energy Specifications	
Energy Cost:	0.0862 CanB/kWh

Results			
Month	Solar Radiation (kWh/m^2/day)	AC Energy (kWh)	Energy Value (CanB)
1	1.25	52	4.48
2	2.42	98	8.45
3	3.36	150	12.93
4	5.27	231	19.91
5	5.90	265	22.84
6	5.89	250	21.55
7	6.68	288	24.83
8	5.89	256	22.07
9	4.94	212	18.27
10	2.52	109	9.40
11	1.48	62	5.34
12	1.13	47	4.05
Year	3.90	2021	174.21

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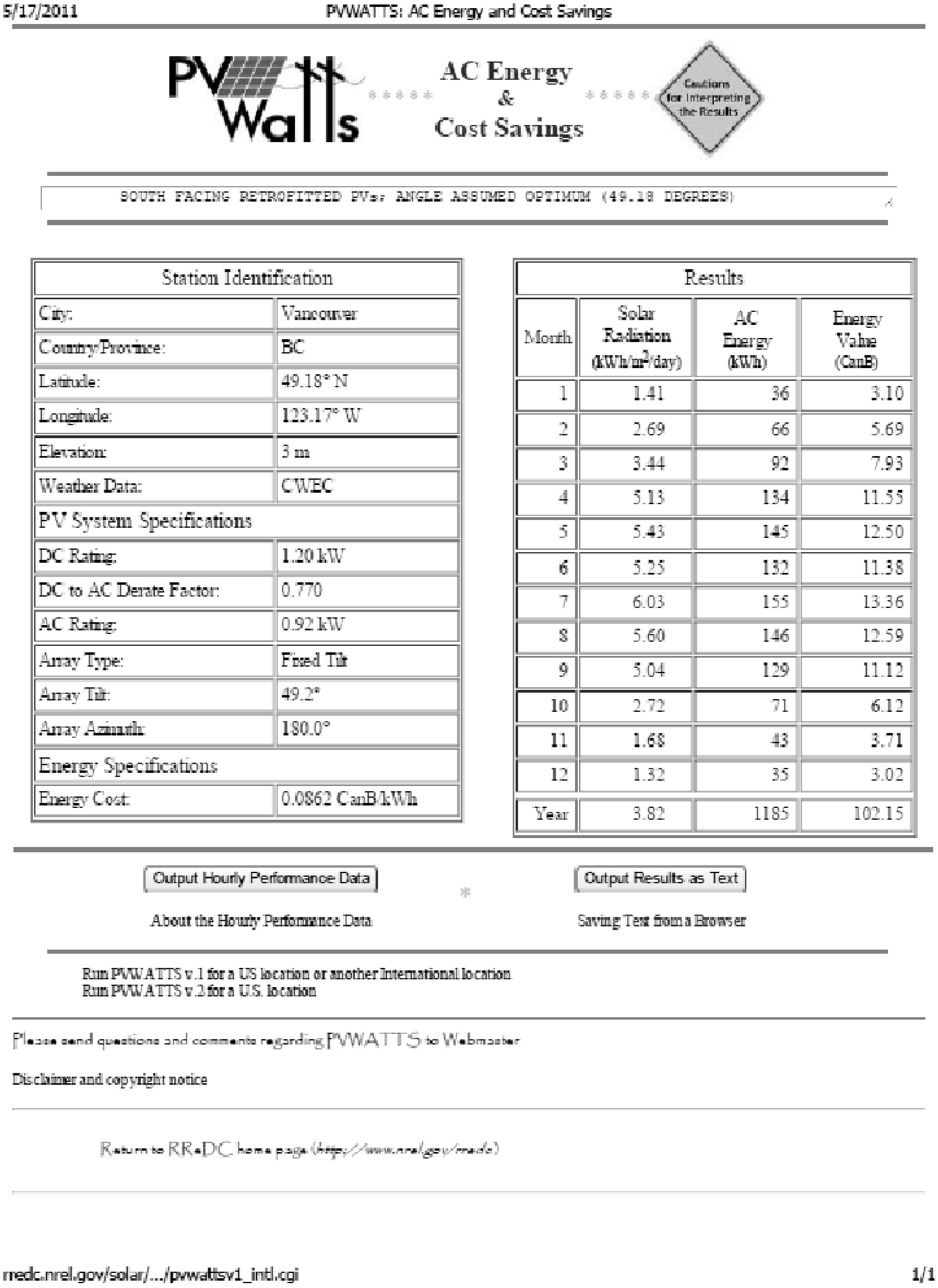
C-3: South Facing Retrofitted PVs – As Installed



5/17/2011 PVWATTS: AC Energy and Cost Savings

SOUTH FACING RETROFITTED PVs; ANGLE ASSUMED OPTIMUM (49.18 DEGREES)

Station Identification	
City:	Vancouver
Country/Province:	BC
Latitude:	49.18° N
Longitude:	123.17° W
Elevation:	3 m
Weather Data:	CWEC
PV System Specifications	
DC Rating:	1.20 kW
DC to AC Derate Factor:	0.770
AC Rating:	0.92 kW
Array Type:	Fixed Tilt
Array Tilt:	49.2°
Array Azimuth:	180.0°
Energy Specifications	
Energy Cost:	0.0862 CanB/kWh

Results

Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value (CanB)
1	1.41	36	3.10
2	2.69	66	5.69
3	3.44	92	7.93
4	5.13	134	11.55
5	5.43	145	12.50
6	5.25	132	11.38
7	6.03	155	13.36
8	5.60	146	12.59
9	5.04	129	11.12
10	2.72	71	6.12
11	1.68	43	3.71
12	1.32	35	3.02
Year	3.82	1185	102.15

About the Hourly Performance Data

Saving Text from a Browser

Run PVWATTS v.1 for a US location or another International location
Run PVWATTS v.2 for a U.S. location

Please send questions and comments regarding PVWATTS to Webmaster

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rredc.nrel.gov/solar/.../pvwattsv1_intl.cgi 1/1

Appendix C - Power Output Hand Calculations

Power Output Calculations

Assumptions:

Solar irradiation in Vancouver 1100 kWh/m^2/year

Performance ratio 0.77

PV module efficiency 0.15

Area for retrofitted PVs is 1m x 1.49 m per module (6 modules) as per spec sheet (assume fully active solar area)

Area for BIPVs is 0.8m x 2.3m per module (18 modules) as measured (not fully active)

$$A_{retro} = 1 \cdot 1.49$$

$$A_{retro} = 1.49$$

$$A_{bipv} = .8 \cdot 2.3$$

$$A_{bipv} = 1.84$$

Power output per m^2

$$P_{retro} = \frac{190}{1.49} \xrightarrow{\text{at 5 digits}} P_{retro} = 127.52$$

$$P_{bipv} = \frac{110}{1.84} \xrightarrow{\text{at 5 digits}} P_{bipv} = 59.783$$

Active area for BIPVs, assuming power output is directly proportional to active area

$$A_{act,\ bipv} = \frac{59.783}{127.52} \cdot 1.84 \xrightarrow{\text{at 5 digits}} A_{act,\ bipv} = 0.86262$$

Yearly Energy Output of BIPVs [kWh]

$$YEO_{bipv} = 1100 \cdot 18 \cdot 0.86262 \cdot 0.77 \cdot .15 \xrightarrow{\text{at 5 digits}} YEO_{bipv} = 1972.7$$

This is close to the ideal calculated value from PVWatts (2021 kWh)

Yearly Energy Output of Retrofitted PVs [kWh]

$$YEO_{retro} = 1100 \cdot 6 \cdot 1.49 \cdot 0.77 \cdot 0.15 \xrightarrow{\text{at 5 digits}} YEO_{retro} = 1135.8$$

This is close to the calculated value from PVWatts (1185 kWh)

Appendix D - Raw Materials

Raw Material Calculations

Assumptions:

Aluminum frame cross section was measured from a similar module to be approximately 108mm^2.
Aluminum density 2700 kg/m^3
Silicon required per watt is 8g/W
Glass is 2mm thick for framed PV, 1.6mm thick for BIPV; density 2500 kg/m^3 ref: [12]
Copper connecting wires weigh approximately 1 kg (measured from similar module)
Substrate found to be approximately 2 kg from literature ref: [12]
EVA film is assumed to be 0.5 kg per module

Aluminum in framed PV:
Mass=Density*Volume= density*(perimeter*cross section + backing plate thickness*PV Area) [kg]

$$V_{alum\ retro} = (2\cdot 1 + 2\cdot 1.49)\cdot 1.08\text{e}{-4} + 0.001\cdot 1\cdot 1.49 \xrightarrow{\text{at 5 digits}} V_{alum\ retro} = 0.0020278 \quad M_{alum} = 0.0020278\cdot 2700 \xrightarrow{\text{at 5 digits}} M_{alum} = 5.4751$$

Silicon in framed PV:
Mass= 8 [g/W]*PV power rating/100 [kg]

$$M_{\text{Si}} = \frac{8\cdot 190}{1000} \xrightarrow{\text{at 5 digits}} M_{\text{Si}} = 1.5200$$

Glass in framed PV:
Mass = thickness*PV Area*density [kg]

$$M_{glass} = 0.002\cdot 1\cdot 1.49\cdot 2500 \xrightarrow{\text{at 5 digits}} M_{glass} = 7.4500$$

Silicon in BIPV:
Mass= 8 [g/W]*PV power rating/100 [kg]

$$M_{\text{Si}} = \frac{8\cdot 110}{1000} \xrightarrow{\text{at 5 digits}} M_{\text{Si}} = 0.88000$$

Glass in BIPV: (two panes per unit)
Mass = 2*thickness*PV Area*density [kg]

$$M_{glass} = 2\cdot 0.0016\cdot 0.8\cdot 2.3\cdot 2500 \xrightarrow{\text{at 5 digits}} M_{glass} = 14.720$$

Appendix E – Transportation

Transportation Calculations

Assumptions:

PV Modules shipped via 3000 TEU container ship from China (Manufacturer) to Vancouver, British Columbia (AFRESH): 5500km; 23 days at sea

GridPoint appliance shipped via semi-truck (0.72 MJ/ton-km) from Montreal, Quebec (Manufacturer) to Vancouver, British Columbia (AFRESH): 4550km

Batteries shipped via semi-truck from Mexico (Manufacturer) to Montreal, Quebec (GridPoint) to Vancouver, British Columbia (AFRESH): 4200km + 4550km

PV Modules

Engine size: 15 MW
RFO fuel energy density 40 MJ/kg
Ship fuel consumption: 190 g/kWh

Energy consumed per hour of sailing [MJ/hr]

$$E_{hourly} = \frac{40 \cdot 190 \cdot 15000}{1000}$$

$$E_{hourly} = 11400$$

Total energy needed for trip: hours per day*days*energy per hour [MJ]

$$E_{total} = 24 \cdot 23 \cdot 11400$$

$$E_{total} = 6292800$$

With 3000 TEU and 1 TEU being 28 m^3; 1 TEU fits 100 packed solar panels safely (from packing box dimensions)
The embodied energy from transportation is: [MJ/unit]

$$E_{pv\ trans} = \frac{62928000\ 1}{3000 \cdot 100} \xrightarrow{\text{at 5 digits}} E_{pv\ trans} = 209.7$$

GridPoint appliance

Unit weight without batteries, inverter and charge controller: 145 kg
Energy for transportation is distance*[MJ/ton-km]*mass [MJ]

$$E_{GP\ trans} = 4550 \cdot 0.72 \cdot 0.145 \xrightarrow{\text{at 5 digits}} E_{GP\ trans} = 475.02$$

Batteries

Battery weight: 57 kg per battery; 16 units (to account for 1 battery replacement)
Energy for transportation is distance*[MJ/ton-km]*mass [MJ]

$$E_{batt\ trans} = (4550 + 4200) \cdot 0.72 \cdot 0.057 \xrightarrow{\text{at 5 digits}} E_{batt\ trans} = 359.1$$

Appendix F - Project Proposal

Project Scope

Project Objective

The objective of this project is to evaluate the effectiveness of the technologies integrated into the BCIT AFRESH Home at generating a net positive energy balance. This will be done using a life cycle energy analysis (LCA) for each system.

Review

The BCIT AFRESH Home was constructed in the year 2000 to showcase sustainable building materials and practices. The letters of AFRESH stand for Accessible and Affordable, Flexible, Resilient, Energy Efficient, Sustainable and Healthy (1). Since its construction, the house has received several energy system retrofits to reduce power consumption from the public grid. In 2006, the house received a photovoltaic energy generation system and a fuel cell distributed energy generation system (2). In 2007, the AFRESH Home was retrofitted with a geo-exchange system to harness geothermal energy (3). This system was also integrated with the fuel cell system to harness waste heat.

Project Specifics

A life cycle analysis will be used to examine the hypothesis that the AFRESH Home is a net energy producer. This will be done by decoupling all the energy generation systems and assessing them as discrete systems.

Justification/Motivation

The current aspirations of the AFRESH Home are to become greenhouse gas neutral and to be a net energy producer. To meet this claim, the AFRESH Home wants to not only generate its own electricity, but generate enough surpluses to account for the energy needed to manufacture, implement and eventually decommission the technologies on site or in other words, recover the embodied energy of the system. To define the embodied energy for the system, the electricity generation systems must be looked at individually to allow for a thorough LCA.

Deliverables

The deliverables of this project are as follows:

- Presentation to Mechanical B.Eng Faculty, students and representatives for the AFRESH Home project detailing the methodology, results, conclusions and recommendations.
- Final report entailing methodology, results, conclusions and recommendations for each of the entire photovoltaic energy system.

Milestone Schedule

See Appendix 1 for the Gantt chart for this project.

Technical Requirement

To ensure the validity of the LCA results, the methodology and guidelines as presented by the International Standards Organization in ISO 14044:2006 (4) and ISO 14040:2006 (5) will be followed.

Limits and Exclusions

The study will be limited to the photovoltaic system as implemented in the AFRESH Home and the environment the AFRESH Home is in. Assumptions, limits and exclusions will depend on the specified boundaries for the system. These boundaries will be implemented according to the project methodology.

Reviews with Stakeholders

The stakeholders for this project have been identified as follows:

Internal:

- Joseph Poon - Faculty, Mechanical Engineering

External:

- Jennie Moore – Director, Sustainable Development and Environmental Stewardship
- Alexandre Hebert - Energy and Sustainability Manager

Weekly progress meetings will be held with the internal stakeholder(s). Meetings will be held with external stakeholders as necessary.

Project Schedule

See Appendix 1 for the Gantt chart for this project.

Project Budget

The budget for this project is limited to printing and stationary costs, as well as fees for research materials. For research materials procured through the Inter-Library Loan system, the fees will be absorbed by the BCIT Library Department (See section 5 for further details). See table 1 below for the full projected budget.

Table 1: Project Budget

Item	Units Req'd	Cost per Unit	Extended Cost	Project Cost
Inter-Library Loans	80	$ 5.00	$ 400.00	$ -
Printing Costs	-	-	$ 100.00	$ 100.00
Billable Hours	150 [hr]	$ 30.00	$ 4,500.00	$ -
Total(s)			**$ 5,000.00**	**$ 100.00**

Project Procurement Plan

Technical reports, journal articles and other research media are to be obtained through the BCIT Library Department if possible. Inter-Library Loan requests for this project do not require Project Advisor approval.

Products will be sourced from local vendors or from product providers on the internet. More expensive, faster shipping methods will only be used with the approval of the project coordinator. Purchase of items more than $50 will require multiple quotes from different vendors. Payments will be made using a BCIT visa card. Criteria that will be used to select products among multiple quotes include, but are not limited to: price, quality, lead time, technical sustainability, technical support, support of local industry and environmental considerations.

Works Cited

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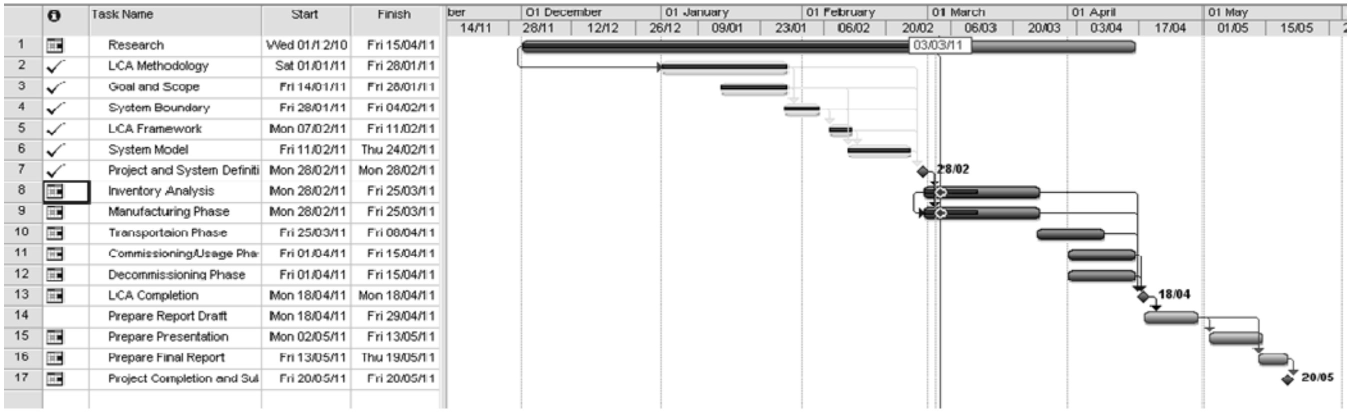
2. **British Columbia Institute of Technology.** BCIT : sustainability : green buildings: sustainable homes. *BCIT.* [Online] nd. [Cited: November 20, 2010.] http://www.bcit.ca/sustainability/operations/buildings/bbyhomes.shtml.
3. **Innotech Control Systems.** Innotech Control Systems - BCIT AFRESH Home Geo-Exchange Retrofit. *Innotech Control Systems.* [Online] 2010. [Cited: November 20, 2010.] http://www.innotech.com.au/Solutions/ProjectDetails.aspx?projid=29.
4. **ISO 14044.** *Environmental management - Life cycle assessment - Requirements and guidelines.* 2006.
5. **ISO 14040.** *Environmental management - Life cycle assessment - Principles and framework.* 2006.
6. **Hebert, Alexandre and Moore, Jennie.** *Project Sponsor Meeting.* November 03, 2010.

Appendix 1- Gantt Chart



	ℹ	Task Name	Start	Finish
1	▦	Research	Wed 01/12/10	Fri 15/04/11
2	✓	LCA Methodology	Sat 01/01/11	Fri 28/01/11
3	✓	Goal and Scope	Fri 14/01/11	Fri 28/01/11
4	✓	System Boundary	Fri 28/01/11	Fri 04/02/11
5	✓	LCA Framework	Mon 07/02/11	Fri 11/02/11
6	✓	System Model	Fri 11/02/11	Thu 24/02/11
7	✓	Project and System Definiti	Mon 28/02/11	Mon 28/02/11
8	▦	Inventory Analysis	Mon 28/02/11	Fri 25/03/11
9	▦	Manufacturing Phase	Mon 28/02/11	Fri 25/03/11
10	▦	Transportaion Phase	Fri 25/03/11	Fri 08/04/11
11	▦	Commissioning/Usage Pha	Fri 01/04/11	Fri 15/04/11
12	▦	Decommissioning Phase	Fri 01/04/11	Fri 15/04/11
13	▦	LCA Completion	Mon 18/04/11	Mon 18/04/11
14		Prepare Report Draft	Mon 18/04/11	Fri 29/04/11
15	▦	Prepare Presentation	Mon 02/05/11	Fri 13/05/11
16	▦	Prepare Final Report	Fri 13/05/11	Thu 19/05/11
17	▦	Project Completion and Sul	Fri 20/05/11	Fri 20/05/11

12 Glossary

AFRESH: Accessible & Affordable, Flexible, Resilient, Energy Efficient, Sustainable, and Healthy. This is the name of the BCIT Home project and the object of this study.

BIPV: Building Integrated Photovoltaic module. In this study, this refers specifically to the east facing photovoltaic modules.

BOS: Balance of System. See Section 4.1.4

CED: Cumulative Energy Demand. See Section 5.1

EPE: Electricity Production Efficiency. See Section 5.3

EPT: Energy Payback Time. See Section 5.2

GJ: gigajoule. Metric measure of energy, one thousand million joules (10^9)

ISO: International Standards Organization. See Section 2.

kWh: kilowatt-hour. Common derived unit for energy consumption

LCA: Life Cycle Analysis or sometimes referred to as Life Cycle Assessment. See Section 2

MJ: megajoule. Metric measure of energy, one million joules (10^6)

NE: Net Energy. See Section 5.4

NPV: Net Positive Value. See Section 5.2

PbA: Lead Acid battery. See Section 6.2.1

PLC: Programmable Logic Controller.

PV: Photovoltaic module

YEO: Yearly Energy Output. See Section 5.2