Trhas Arefayne Asmelash

Life Cycle Assessment of Building Integrated Photovoltaics for Zero Emission Buildings

Author:Trhas Arefayne Asmelash
Supervisor: Helge Brattebo
Co-supervisor: Bjørn Peter Jelle

Norwegian university of Science and Technology
Faculty of Engineering Science and Technology
Department of Energy and Process Engineering

NTNU – Trondheim
Norwegian University of Science and Technology

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NTNU
Det skapende universitet

MASTERKONTRAKT

- uttak av masteroppgave

1. Studentens personalia

Etternavn, fornavn	Fødselsdato
Arefayne, Trhas Asmelash	**04. jun 1981**
E-post **trhasaa@stud.ntnu.no**	Telefon **41187384**

2. Studieopplysninger

Fakultet	
Fakultet for ingeniørvitenskap og teknologi	
Institutt **Institutt for energi- og prosessteknikk**	
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3. Masteroppgave

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Oppgavens (foreløpige) tittel
Life cycle assessment of building integrated photovoltaics for Zero Emission Buildings

Oppgavetekst/Problembeskrivelse
The objective of this master thesis is to contribute to the understanding of environmental life cycle assessment (LCA) on the use of building integrated photovoltaics (BIPV) within the Zero Emission Building concept. The thesis will examine a few selected BIPV solutions within, in collaboration with on-going research at SINTEF Building and Infrastructure, and at Department of Civil and Transport Engineering, NTNU. The following tasks are to be considered:

1. Carry out a literature study on state-of-the-art strategies, technologies and/or methods that are relevant for your work.
2. Provide a systems definition of the system you are analysing, including description of goal and scope, system boundaries, data inputs and assumptions, for selected scenarios and/or configurations of technological solutions within your system.
3. Develop a quantitative model for your system, including relevant indicators and/or metrics that can be used to document the environmental performance of the system.
4. Report results from the environmental performance analysis of your system (including scenarios and/or configurations of technological solutions) and the role of critical system variables, ...

Hovedveileder ved institutt	Medveileder(e) ved institutt
Professor Helge Brattebø	**Bjørn Petter Jelle**

Merknader
1 uke ekstra p.g.a påske.

4. Underskrift

Student: Jeg erklærer herved at jeg har satt meg inn i gjeldende bestemmelser for mastergradsstudiet og at jeg oppfyller kravene for adgang til å påbegynne oppgaven, herunder eventuelle praksiskrav.

Partene er gjort kjent med avtalens vilkår, samt kapitlene i studiehåndboken om generelle regler og aktuell studieplan for masterstudiet.

Trondheim 1/6 - 15
....
Sted og dato

.... **Student**

.... **Hovedveileder**

Originalen lagres i NTNUs elektroniske arkiv. Kopi av avtalen sendes til instituttet og studenten.

Abstract

In this thesis the life cycle of a building integrated PVs has been evaluated to estimate the life cycle CO_2 emissions and other relevant impact categories of multi and mono-si wafers. The environmental impact for producing a unit square meter of BIPV multi and nono-si wafers are also analyzed. In addition, the five common types of impact categories of, Climate change, Ozone depletion, Human toxicity, Particulate matter formation and Fresh water ecotoxicity, were analyzed in view producing the functional. By comparing the life cycle assessment of the two PV types, the electricity generated by Mono-si results more of pollution compared to Multi-si wafer. Moreover, PV sizing analysis has been made by considering a household functional unit. The sizing analysis has considered six poli si and one mono si PV modules.

Preface

This thesis has submitted in partial fulfillment of the requirement for the degree of Master of Science in Industrial ecology, at Norwegian University of Science and Technology (NTNU). The thesis has been performed at the Department of Energy and Process Engineering in the faculty of Engineering Science and Technology with Professor Helge Brattebo as main supervisor and Bjørn Peter Jelle as co-supervisor. The thesis work has been carried out between 09-March 2015 and 03 August 2015, which was continued from where it stopped in 2014 due to sickness, pregnancy and maternity leave. Although, the first agreement of the thesis discusses the paper was supposed to be written in paper; the paper is written in the present form in consultation with the main supervisor and due to lack of time and less interest from the co-supervisor.

Acknowledgement

Above all, I thank my God for giving me all the strength and courage during this period of challenges. Next, I am very pleased to thank all the people who in one way or another helped me to successfully accomplish my study. Especially; I would like to express my profound and sincere gratitude to my supervisor, Professor Helge Brattebo, for his best supervision and advice from the beginning till the end of the thesis work. His valuable guidance was a prime mover for my daily activities. I am very grateful for his all-round assistance, and fatherly type approach.

I am very grateful to the help I received from the International office and energy and process engineering department.

It is an honor for me to express my sincere gratefulness to my father, my mother, my brothers and sisters for their support and love. I am especially grateful to my wonderful and caring father Arefayne A. Gebrewahid for his efforts and encouragement all the way in my life. This is a great reward for him to see the result of his inspiration. Dad your inspiration and dedication were my springboards in every step of my careers, Thank you very much and God bless you.

This theis work would have not been possible without the love, support and encouragement of my beloved husband Dr. Asfafaw H Tesfay and my beautiful daughter Nolawit. Your support, passion and love have been my energizer all the way throughout this work. Asfafaw, I owe you my heart-felt appreciation for devoting yourself and time to taking care of the family during this time. You are the most important person in my life and I will always love you. Nolawit, you made our home very enjoyable with your entire activities, fun and your lessons. Nathan and Nuhamin you came in the right time and you made Nolawit happy by sharing her loneliness, I love you all and God bless you.

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1. Introduction

1.1. Motivation and context

This section provides the motivation and content of the thesis related to energy consumption in buildings, zero energy buildings (ZEB) and the corresponding life cycle impacts.

Increasing energy demand derived from population growth, economic development, sharp increase in oil prices and the increase problem of greenhouse gases have demonstrated to be deemed the importance of forming diversified energy profiles. [1] illustrates the importance of renewable energies, today diversifying the power supply to include more and more of renewable energy sources is becoming a recommendable and common strategy practice in many parts of the world. Protecting global warming, infinite energy supply, energy securities, and economic wise are the positive externalities caused a worldwide interest on renewable energies [2].

According to the European commission 2009 report, climate change is one from among the major problems that our world is facing today. For instance, to alleviate this problem and keep the global temperature below two degree Celsius of the pre-industrial level, the European Union has been set an ambitious long term target as well as a host of accompanying policies. Sharing 20% of renewable energy in the primary energy consumption is one from the many targets [3]. To cope up this challenge, solar photo voltaic (PV) is one of the supreme type of renewable sources of energy in solving these problems [4].

Power generation from photovoltaic is one of the promising renewable energy resource over the conventional technologies for electricity generation. During the use phase, PV is generally environmental friendly with no toxic gas emissions or chemical pollutants, no noise generation [4]. In addition to those facts, globally the demand and technologies of PVs are growing rapidly, especially for building integrated photovoltaic (BIPV), which is gaining worldwide acceptance [5].

Zero emission buildings (ZEB) with BIPV comprises a group of PV technologies that is associated in the building elements, replacing part of the building such as conventional roof tiles, glazing, facades, etc. Due to cost reduction of the building materials during the construction phase, and eliminating the need for separate support structure or additional land use over the conventional ground mounted PV panels, BIPV panels are cost effective at the same time reduces environmental loads by reducing the use of fossil fuels and other energy sources that could rise environmental pollution during their use phase [6]. However, any energy production technology, no matter how green it is, may lead to environmental impacts over its entire life cycle [7]. Therefore, it is necessary to apply an LCA tools. By doing so the LCA result will show the impact of the considerable amount of material inputs and energy consumption over the entire life cycle of PVs.

Several studies have indicated that Energy Payback Time (EPT) as one of LCA's indicator, which investigates the time taken by the panel to generate the same amount of energy required for its manufacture. Carbon footprint and geographical difference are also stated as another LCA indicators that give interest of other studies in analyzing the environmental impact of different energy sources. Different studies have used various PV technologies to analyze the LCA of PV. These includes: amorphous silicon (a-si), CdTe thin film (CdTe), CIS thin film (CIS), single-crystalline and poly-crystalline that are integrated with the building or in the form of ground mounted. Various studies interested in some advanced solar cell systems like: high-concentration PV, heterojunction solar cells and dye-sensitized solar cells were discussed in terms of environmental impacts, energy requirements and energy payback time during the life time of the products. In this thesis, the findings of some literatures with these perspectives are summarized below.

The environmental impact of PVs with regard of geographical difference and comparison with other energy sources has been concluded as: PVs have some environmental advantages as compare with the conventional power plants, and this analysis is quite dependent on the environmental indicators. However, as PVs are compared with other renewable sources of energy e.g. wind and hydropower, they have environmental inconveniences. Regional conditions such as, solar irradiation or technology standards are some of the reasons that brings the differences. In the case of different PV technologies, the total life cycle greenhouse gas (GHG) emissions of CdTe Vs Si PVs have different environmental impacts as different geographical diversity is taken in to account. Like, CdTe PVs modules made in U.S. have environmental advantages over silicon ones. However, this result is no longer valid as it is compared to the CdTe PVs produced in China. The GHG emissions of CdTe PVs made in china is much higher over the Si PVs and slightly larger as compared with ribbon-Si PV that is made in Europe. Therefore, production location of PVs is the major factor that is mentioned in these analysis. In spite of this fact, CdTe PVs have better environmental performance and energy sustainability over the other PV technologies [8].

In this study, an LCA analysis of two BIPV types is conducted, which includes material inventory and the summary of the energy use and GHG emissions during the life cycle of the facility.

1.2. Objectives, research questions and scope of the study

The background for this thesis is the current high priority of research and development (R&D) and practical implementation of new solutions for minimizing energy consumption of buildings, and the corresponding expected environmental life cycle impact reductions. Within this priority the framework of Net Zero Energy Buildings (Net ZEB) facilitates solutions aiming to balance the following two actions:

1. Reduced energy demand by means of energy efficiency measures, and
2. Generate electricity as well as thermal energy carriers by means of energy supply options to get enough credits to achieve the balance of Net ZEB. In order to reach these goals there are numerous possible solutions that may be used, and combined, in practice.

1.2.1. Objective

The global objective of this master thesis is to contribute to the understanding of environmental life cycle assessment (LCA) of Net ZEB concepts.

The specific objective is to examine selected PV technology alternatives within the Net ZEB framework, in collaboration with on-going research at SINTEF Byggforsk, and analyze the contribution of PV source to the total energy demand of a Norwegian household.

1. Examine the efficiency of PV solutions (mono and multi silicon PV)
2. Estimate energy demand (energy delivery)
3. Estimate PV size of households
4. Analyze the LCA performance of PV solutions for this case study
    a. Analyze the LCA of Mono-silicon PV modules
    b. Analyze the LCA of Poly-silicon PV modules

1.2.2. Scope

The scope of the thesis work includes the following tasks:

1. Carry out a literature study on state-of-the-art strategies, technologies and/or methods that are relevant for the work.
2. Provide definition of the system under analysis, including description of goal and scope, system boundaries, data inputs and assumptions, for selected scenarios and/or configurations of technological solutions within the selected system.
3. Develop a quantitative model of the system, including relevant indicators and/or metrics that can be used to document the environmental performance of the system.
4. Report results from the environmental performance analysis of the system (including scenarios and/or configurations of technological solutions) and the role of critical system variables, components or assumptions leading to these results.
5. Finally, discuss the overall findings of the study in agreement with the literature review, strengths and weaknesses of the methods used in this study, and possible practical and/or methodological implications and recommendations based on the results.

1.3. Assumption and limitation

The LCA analysis of the thesis is made by taking the following assumptions:

- Multi and Mono-si wafers
- The wafer thickness is considered as 240 and 270 um for Multi and Mono-si wafers respectively
- A functional unit of unit square meter is considered
- Some materials are taken from Simapro material data base during analysis(ecoinvent)
- Material inputs such as polyethylene glycol (PEG), steel wire, poly-si were replaced by triethylene glycol, steel and multi-si respectively

The main limitations in this study was

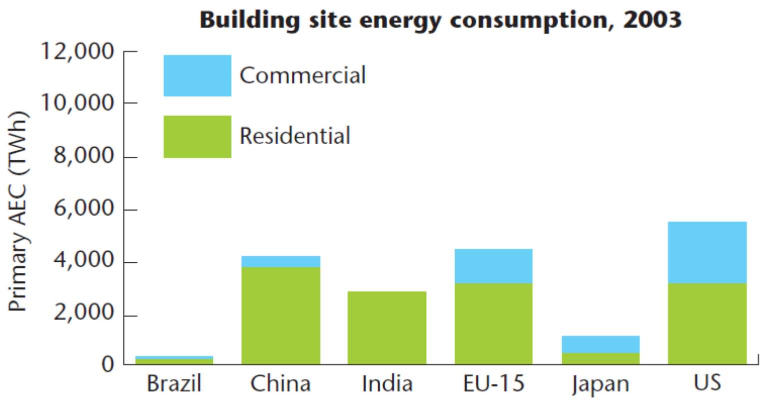
- It was hardly difficult to get the life cycle inventories that has been used in producing the PV wafers
- it was hardy difficult to find a similar and a replaceable material inputs of quartz crucible and factory area and have been omitted in the analysis
- Difficulties to access the soft simapro software via VPN connection
- Though in the master contract was agreed to submit the Master's thesis in paper format, due to maternity leave and time limit, I have submitted in

2. Literature review

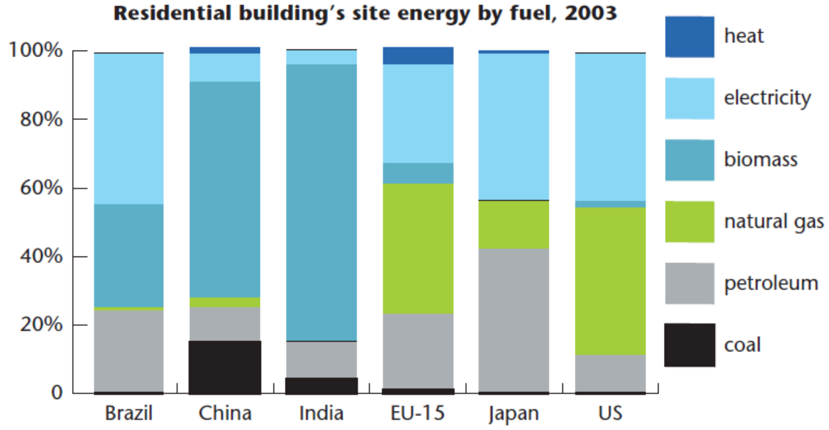
2.1. Energy consumption of buildings

With the growing global demography, the number of urban dwellers is increasing rapidly and it is expected to reach five billion or 60% of the total population by 2030 [9]. Accordingly, energy demand in cities should be a dominant issue in energy supply planning. The increasing energy consumption demand by urban populations in residential sector could affect economic development by limiting the energy demand of productive sectors, which use energy to produce goods and services. However, increasing energy supply only cannot solve the current energy supply and security situation and its associated environmental problems. Nevertheless, the problem can be addressed with respect to climate change and resource shortage approaches, making residential and non-residential buildings more energy- and resource-efficient while maintaining their thermal comfort and cost-effectiveness to save money and reduce pollution. Today buildings account for about 40% of final energy consumption worldwide, and they are responsible for about one third of overall CO_2 emissions [10]. Building energy consumption in urban structures is typically twice as high as transport and its energy saving potential is large. The European Union has set a target of 20% building energy savings up to 2020 and to develop climate neutral buildings at the end of 2050 [11]. This target helps to reduce CO_2 emissions between 12% and 25% caused by heating and cooling and between 13% and 52% caused by electric lighting and equipment respectively. The building sector has been identified as one of the key sectors to achieve the 20/20/20 targets of the EU. The target states that 20% of greenhouse gas emissions compared to 1990, 20% energy savings by 2020 (compared to a business as usual scenario) and 20% share of renewables in 2020) [12].

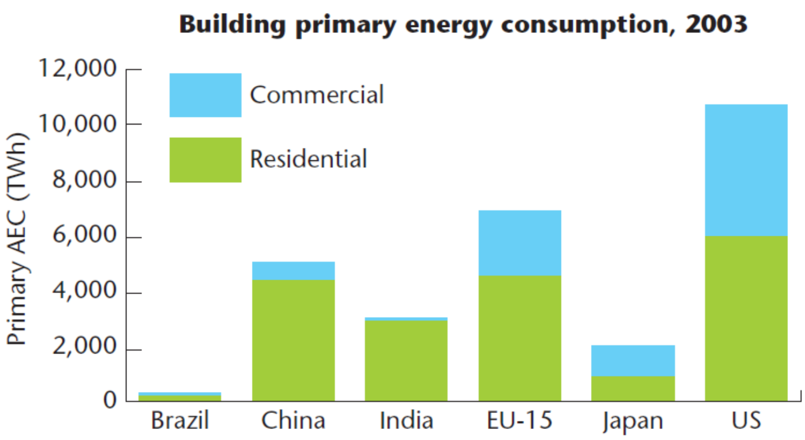
Energy is used in buildings to get different services such as comfort and hygiene, food preparation and preservation, entertainment, and communications. The level of service and the quantity and quality of energy used for these purposes depends on the overall developmental level of users. Today the level and type of energy use in buildings is affected by culture, family size, construction material, fuel type, technology, user behavior etc. Figure 1 shows the pattern of energy use in commercial and residential building and the type of source they used to satisfy this need.


Building site energy consumption, 2003
Primary AEC (TWh)
12,000
10,000
8,000
6,000
4,000
2,000
0
Commercial
Residential
Brazil
China
India
EU-15
Japan
US

(a)


Residential building's site energy by fuel, 2003
100%
80%
60%
40%
20%
0
Brazil
China
India
EU-15
Japan
US
heat
electricity
biomass
natural gas
petroleum
coal

(b)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12,000
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Brazil
China
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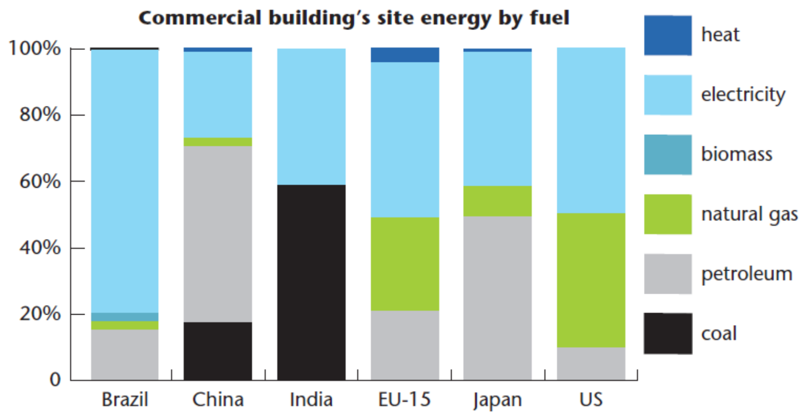
EU-15
Japan
US

(c)



(d)

Figure 1: Building final and primary energy use in selected countries in 2003 [13]

Generally buildings primary energy is mainly consumed for the following applications

- Thermal comfort: used for space conditioning (heating, cooling and ventilation)
- Illumination: use of different lighting sources
- Sanitation and hygiene: use of water heater, washing machine, ironing and dishwashing
- Communication and entertainment: use of televisions, computers, and office equipment
- Food preparation and storage: use of refrigeration and cooking

The need and level of energy use in buildings have a dynamic nature and it is influenced by the following factors: service demands:

- Demographic growth
- Urbanization
- Energy shift from primary to modern commercially available energy sources
- Individual income
- level of economic development
- Cultural features
- Level of technological development; and
- User (individual) behavior

The energy service has also varied between commercial (offices, marketing, restaurants, hotels, schools, hospitals) and residential buildings (single and large family). The amount of energy used within buildings is also affected by the approaches, standards and technologies by which the buildings are sited, designed, constructed, operated, and utilized. Most of all, the level of economic development shows different energy use in buildings. Table 1 shows the variation of energy use per capita in buildings in different representative countries. The figures of the table shows that how the level of economic development of a country affects its energy use.

Table 1: Contribution of the buildings sector to the total fi nal energy demand globally and in selected regions in 2007 [13].

World regions	Share of the residential sector in %	Share of the commercial sector in %	Share of the total buildings sector in %	Residential and commercial energy demand per capita, MWh/capita-yr.
USA and Canada	17%	13%	31%	18.6
Middle East	21%	6%	27%	5.75
Latin America	17%	5%	22%	2.32
Former Soviet Union	26%	7%	33%	8.92
European Union-27	23%	11%	34%	9.64
China	25%	4%	29%	3.20
Asia excluding China	36%	4%	40%	2.07
Africa	54%	3%	57%	3.19
World	23%	8%	31%	4.57

Figure 2 shows a review of household energy services analyzed on a life cycle basis and it shows buildings related energy use contributes 60–70% of the total household energy use in some selected countries and up to 90% in India.

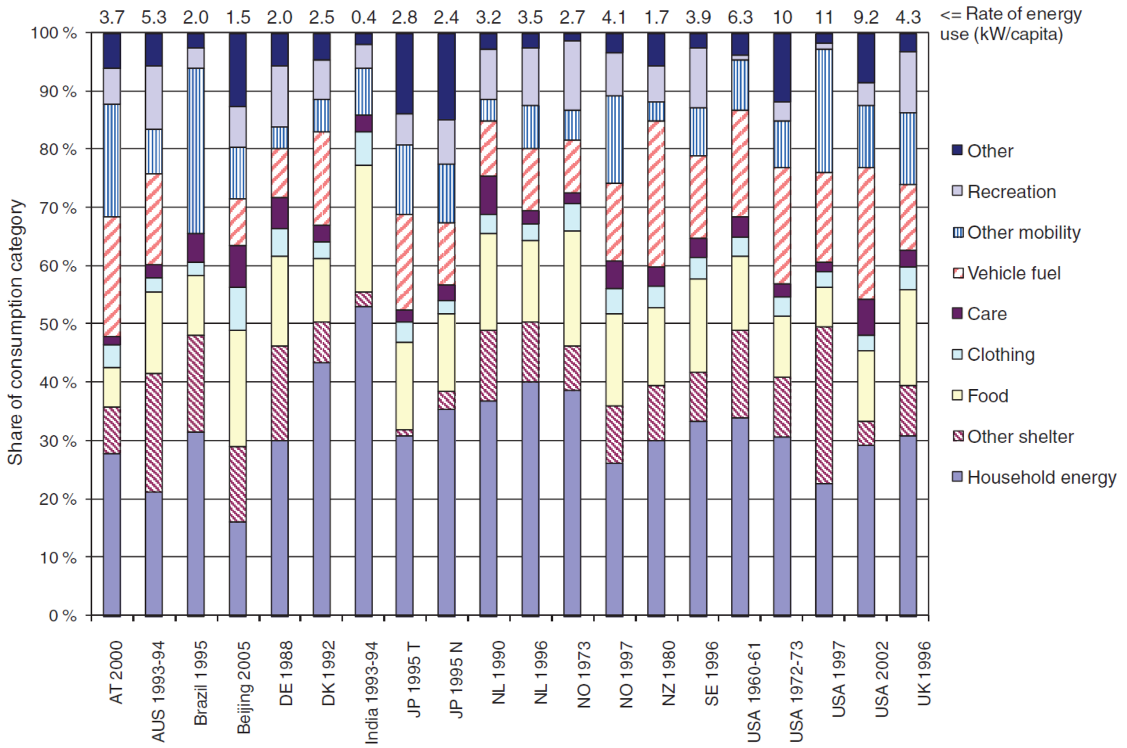


Figure 2: Share of consumption categories in total energy use based on life-cycle analysis or input-output calculation and rate of annual energy use in kilowatt per capita(numbers on top of the columns). Source: Hertwich, 2011 [13].

2.2. Indirect Energy Use from Activities in Buildings: LCA Approach

Life cycle assessment is necessary to optimize the total energy requirement of buildings by incorporating indirect energy use. According to the 2012 IEA report, smart building constructions can contribute as much as 25% of total indirect energy. BIPV systems require at least five years to recover the energy invested in their construction and may not be the cleanest option of supplying electricity from LCA's perspective [14]. Environmental impacts of different building materials and designs depend on a number of factors such as carbon storage and potential energy recovery after demolition. Renewal of existing building designs increase energy efficiency and offer savings in total life cycle energy use compared to demolition and new construction. Generally, significant reduction of environmental impact from buildings can be found by combining energy efficient building design, wise choice of building materials, and renewable energy sources integrated in these buildings.

A life cycle approach is necessary to optimize the total energy use required to provide energy services in buildings. In addition to direct energy use, a life cycle approach considers the energy used to produce construction materials for the building, energy losses associated with the provision of electricity and fuels to the buildings, energy used in the construction and maintenance of a building, and energy used in manufacturing and supplying building equipment such as lighting, TV sets, heating and cooling equipment [15].

2.2.1. The Life Cycle Impact of Building Materials and Design

The level of energy use in buildings has a distinction between construction, operations, maintenance, and demolition. Since for most buildings the bulk energy use is in operations phase, energy conservation efforts should suitably focus on reducing this energy by incorporating smart design, better insulation material, and improved building technology. Similarly, in short-lived or highly efficient buildings; construction took substantial share of the total energy use. On the other hand, demolition gives a chance to recover some of the energy, either by combusting or by reusing building materials and components, which avoids energy-intensive production of new materials. In construction, and especially demolition, energy for transport is an important consideration, constraining remanufacturing and recycling of building components and materials.

2.2.2. Life Cycle Energy and Emissions of Residential Appliances

The electricity, used by electric and electronic products, used in buildings is eventually converted to heat and then this heat either contributes to heating the building or removed through a cooling system depending on the buildings environment. This energy use in office buildings is estimated to several 100kWh/m2/yr, electricity consumption in residential buildings in OECD countries is about 50kWh/m2/yr [13]. LCA of large appliances indicate that operations-phase electricity use is the dominant source of environmental impacts [16]. Nevertheless, personal computers; production causes significant impacts [17]. A study of life cycle impacts of household appliances and electronic equipment [13], shows that the GHG emission caused by the production of information and communication technology and audiovisual equipment purchased by Norwegian households is larger than the emissions caused by the electricity these equipment uses as shown in Figure 3. The study further indicates that the GHG emissions caused by manufacturing of the equipment and the use of networks and content of ICT and audiovisual equipment are equal to or larger than the emission caused by washing machines, driers, refrigerators, and freezers taken together.

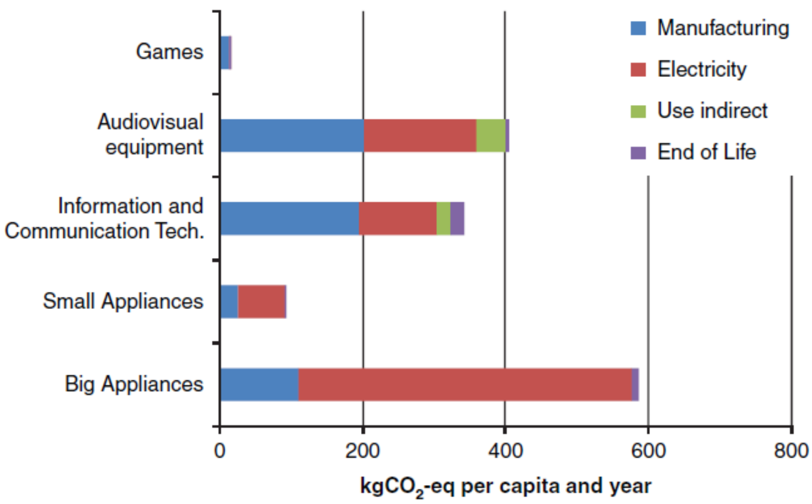


Figure 3: GHG emissions associated with the purchase, use and disposal of electric and electronic equipment in Norwegian households [13].

2.3. The Impact of a Changing Climate on Building Energy Service Demand

A warming and changing climate has a strong influence on energy use in the building sector worldwide. While cooling demand increases as the climate warms, passive cooling approaches become less effective or do not achieve acceptable indoor temperatures. On the other hand, heating demand decreases in cold zones and allows acceptable winter comfort to be achieved more easily. In temperate climate areas such as much of Europe, Japan, South Africa, or the United States, both impacts on winter heating and summer cooling demand can be observed.

The net impact of warming depends on a complex set of factors. These includes: choice of fuel and conversion efficiencies for heating fuels and power generation, building design, efficiency, and operation. Cooling loads will depend strongly on the market penetration of air conditioning, which itself will be dependent on income, building design, culture, and increasing internal loads of buildings by office automation as well as external temperature. Furthermore, the cooling demand is intensified by urban heat island effect and by the growth of service demand for cooling. In some moderate climate regions, heating loads may decrease substantially, or may even become unnecessary due to the combined effect of advanced knowhow in building construction, building insulation performance, and increased in internal heat loads. On the other hand, the load on refrigeration equipment increases and its efficiency decreases with rising internal temperatures. Therefore, the overall global effect of climate change is very likely to be an increase in electricity use, due to additional cooling demand in warmer continents and regions, despite a reduction in direct heating fuel use, with a net impact on primary energy that depends on a range of factors [18].

Similarly, changes in summer temperatures tend to increase a maximum load on electricity systems that already have summer peak demand and increase the need for power generation capacity. There are also implications for cooling strategies in buildings in some cold moderate climates, where residential building over-heating is currently not a significant issue. And passive cooling techniques currently associated with warmer climates will be incorporated into building design. In some arid climates on the other hand, existing passive cooling techniques become inadequate and show greater reliance on active cooling. Generally, building designs will need to allow comfortable conditions in the range of climates they are expected to face over a building's lifetime. If this transformation is not happened, there will be increased mortality and health risks from heat stress.

Following this fact, studies indicated that the total electricity demand in the buildings sector is projected to slightly decrease in Nordic and Baltic countries by 0.5% and increase by 7% in southern Greece, Malta, Cyprus, Southern Italy, Spain, and Bulgaria by 2050 [19].

2.4. Zero energy buildings

A zero-energy building, also known as a zero net energy (ZNE) building, net-zero energy building (NZEB), or net zero building, is a building with zero net energy consumption, meaning the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy generated on the site. These buildings still produce greenhouse gases because on cloudy (or non-windy) days, at night when the sun isn't shining, and on short winter days, they use conventional grid power as their main energy source. Because of this, most zero net energy buildings still get half or more of their energy from the grid. Buildings that produce a surplus of energy over the year may be called "energy-plus buildings" and buildings that consume slightly more energy than they produce are called "near-zero energy buildings" or "ultra-low energy houses".

Most zero-energy buildings use the electrical grid for energy storage but some are independent of grid. Energy is usually harvested on-site through a combination of energy producing technologies like solar and wind, while reducing the overall use of energy with highly efficient HVAC and lighting technologies. The zero-energy goal will become more practical when the cost of alternative energy reduced and the cost of traditional fossil fuels increase.

The development of modern zero-energy buildings became possible not only through the progress made in new energy and construction technologies and techniques, but it has also been significantly improved by academic research, which collects precise energy performance data on traditional and experimental buildings and provides performance parameters for advanced computer models to predict the efficacy of engineering designs. Zero Energy Building is considered as a part of smart grid. Some advantages of these buildings are as follow:

- Integration of renewable energy resources
- Integration of plug-in electric vehicles
- Implementation of zero-energy concepts

The zero-energy concept allows for a wide range of approaches due to the many options for producing and conserving energy combined with the many ways of measuring energy (relating to cost, energy, or carbon emissions) [20].

Zero energy buildings are described as buildings that have zero carbon emissions on an annual basis. In practice, this is achievable by reducing the energy demand of the building and by exploiting renewable energy sources (RES) using appropriate technologies to satisfy the reduced energy requirements. The ZEB principle is anticipated to contribute significantly towards the achievement of the future smart cities, envisioned by the European Union and promoted through its regulatory framework. According to the recast of the directive on the energy performance of buildings (Directive 2010/31/EU), all new buildings ought to be nearly zero-energy from 2020, while the new public buildings should set the example by complying with this requirement two years in advance. In addition, the Commission encourage member states to develop policies, financial measures and other instruments for the promotion of the cost-effective transformation of all existing buildings into nearly ZEBs. Moreover according to the European Strategic Energy Technology Plan (SET-Plan), at least half of the existing buildings in 25 demonstration cities are required to be transformed into nearly zero energy buildings by 2020. The SET-Plan and the "Smart Cities & Communities Initiative" encourage cities and regions to progress by 2020 towards a 40% reduction of GHG emissions through the sustainable use and production of energy [European Commission, 2009]. The SET-Plan anticipates that at least 25 European cities will be at the forefront of the transition to low carbon economies by 2020. Therefore, the SET-Plan funds ZEB demonstration projects for new and existing buildings, as well as additional projects for the exploitation of RES for heating and cooling purposes, the development of smart grids, and the promotion of alternative fuel vehicles and sustainable mobility [21].

In February 2009, the research council of Norway assigned the faculty of architecture and fine art at the Norwegian University of Science and Technology to host the Research Centre on zero emission buildings, which is one of eight new national Centers for environment-friendly Energy Research (FME). The main objective of the FME-centers is to contribute to the development of good technologies for environmentally friendly energy and to raise the level of Norwegian expertise in this area. In addition, they should help to generate new industrial activity and new jobs. Over the next eight years, the FME-Centre ZEB will develop competitive products and solutions for existing and new buildings that will lead to market penetration of zero emission buildings related to their production, operation and demolition [22].

2.5. Net zero energy buildings (Net ZEB)

A net-zero energy building (NZEB) is a building with zero net energy consumption, i.e. the total amount of annual energy use of the building is roughly equal to the amount of renewable energy generated on the site. Such buildings consequently do not increase the amount of GHG in the atmosphere. Most NZE buildings get half or more of their energy from the grid, and return the same amount at other times.

Traditional buildings consume significant amount of fossil fuel energy in developed countries and they are significant contributors of GHG emission. The net zero energy consumption principle is seen as a means to reduce carbon emissions and reduce dependence on fossil fuels although zero-energy buildings remain uncommon. However, they are gaining importance and popularity. Most ZE buildings use the electrical grid to store energy, however, some are stand alone. Energy is usually harvested on-site through a combination of energy producing technologies, but it is possible to reduce the overall energy use with efficient heating ventilation and air conditioning (HVAC) and lighting technologies. The ZE target is getting practical with decreasing costs of alternative energy technologies and increasing the costs of traditional fossil fuels. The development NZEBs became possible not only because of the progress in new energy and construction technologies, but it has also been enriched by research.

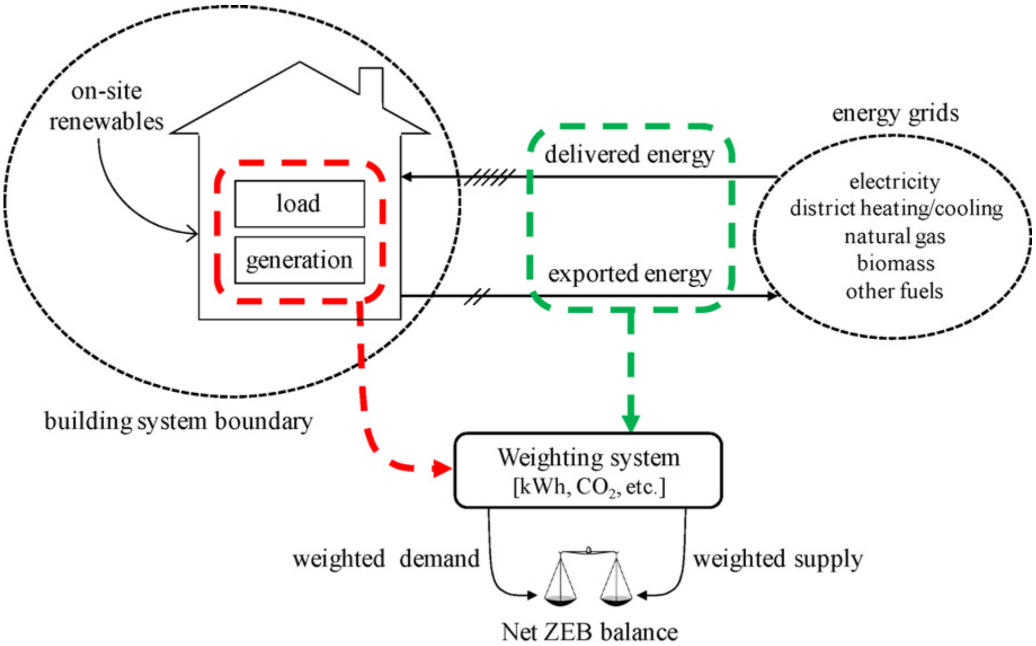


Figure 4: Sketch of connection between buildings and energy grids showing relevant terminology [6]

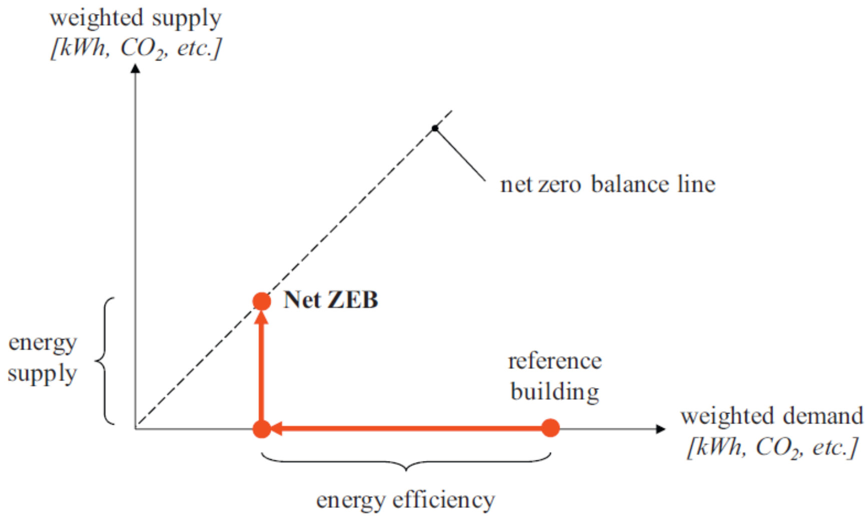


Figure 5: Graph representing the net ZEB balance concept [6]

Norway's national target towards nearly zero energy buildings (Intermediate and 2020) for improved energy performance of new and existing buildings undergoing major renovation [23]. The national plan on how to increase the number of buildings which have to be built in line with the concepts and definitions of NZEB. In this thesis information's related to Energy

Performance of Buildings Directive (EPBD) of national plans – or information elements which are considered to be part of a complete EPBD national plan are given respectively.

- Major renovation of existing buildings
  - Low energy standards by 2015 (public buildings from 2014)
  - Passive House standard by 2020 (public buildings from 2018)
- New constructions
  - Passive House standard by 2015
  - Nearly Zero Energy standard by 2020 (public buildings from 2014)

2.6. Norway's NETZEB Target

Norway's ZEB project has set four different ambition levels [24], which are:

a. ZEB-O÷EQ: Emissions related to all energy use in operation (O) except energy use for equipment/appliances (EQ) shall be compensated with on-site renewable energy generation. Energy use for equipment is often regarded as the most user-dependent and most difficult to design for low energy use.
b. ZEB-O: Emissions related to all operational energy (O) shall be compensated for with on-site renewable energy generation as well as energy use for equipment.
c. ZEB-OM: Emissions related to all operational energy (O) use plus embodied emissions from the materials (M) and technical installations shall be compensated for with on-site renewable energy generation.
d. ZEB-COM: The same as ZEB-OM, but also taking into account emissions related to the construction (C) process of the building.

According to the EN15978 (2011) standard the "M" in the ZEB-OM stands for compensating for emissions related to the product phase of materials, A1–A3, and the product phase for scenarios for the replacement phase, B4. Further, it is suggested that the ambition level ZEB-COM includes the same phases as ZEB-OM, in addition to the emissions from the construction process where both A4, transport to building site, and A5, construction installation processes, are included and need to be compensated for.

Later, further detail analysis on ZEB has expanded and the ambition level is suggested to include ZEB-COME and ZEB-COMPLETE. ZEB-COME should include the same as level ZEB-COM, in addition to scenarios for the end-of-life phases, C1-C4. The highest ambition level, ZEB-COMPLETE, should be based on an emission analysis that includes all the phases: A1–A5, B1–B6 and C1–C4, with scenarios for B2, B3 and B5 on maintenance, repair and refurbishment.

i. ZEB-COME: Same as ZEB-COM though emissions related to a scenario for the end-of-life phase "E" have to be included and compensated for (phases A1-A5, B4, B6, C1, C2,C3 and C4 from the standard EN15978 (2011)).

ii. ZEB-COMPLETE: Emissions related to a complete life cycle emission analysis have to be compensated for, namely all the phases, A1–A5, B1–B5, as well as B6- operational energy use and C1–C4, from the standard.

Table 2: Different stages of the life cycle of a building [24]

A1-3			A4-5		B1-5					C1-4				Supplementary Information beyond the building life cycle. D
Product stage			Construction stage		Use stage					End of life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction installation process	Use (B6 operational energy use and B7 operational water use)	Maintenance	Repair	Replacement	Refurbishment	Deconstruction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling potential

The report also divided the different life cycle stages into four main phases:

- Product stage (A)
- Use stage (B)
- End-of-life stage (C)
- Benefits and loads beyond the system boundary (D)

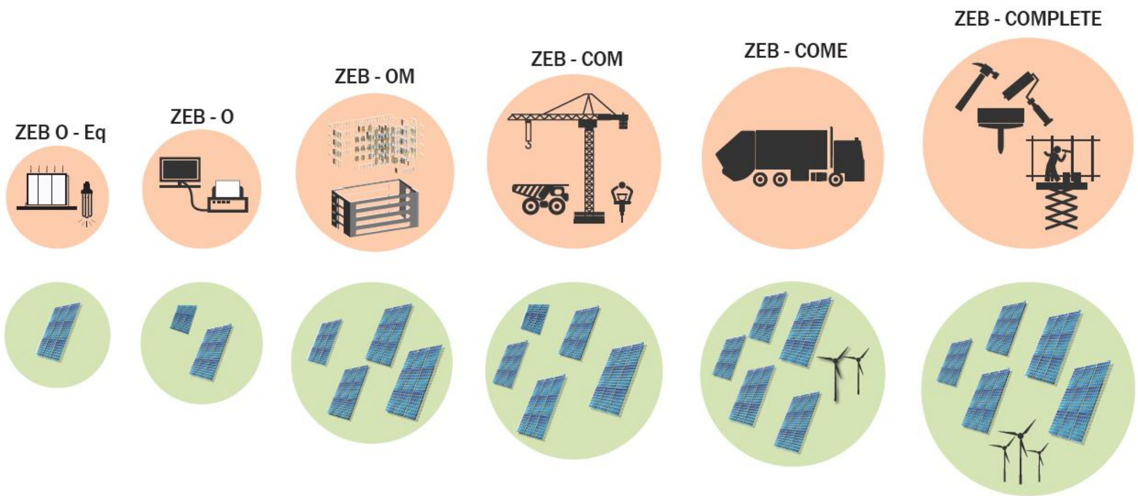


Figure 6: Illustration of the different levels with increased inclusion of life cycle phases and increased production of renewable energy on site [24]

2.7. PV-system (BIPV)

By far crystalline silicon modules are the most largely used and most extensively studied PV type. Table 2 shows a summarized results of conventional, environmental, LCA and it also presents the hypotheses considered for the LCA analysis.

2.7.1. PV selection

There are countless end uses of PV, with a broad variety of system complexity. A range of applications is shown in the chart of Figure 7. On-grid versus off-grid applications share certain characteristics but the PV systems satisfy distinctly different needs. For example, both on-grid and off-grid PV systems may use the same module technology, mounted in the same manner, deployed in the same climate, and deliver the same amount of AC energy to a hypothetical customer.

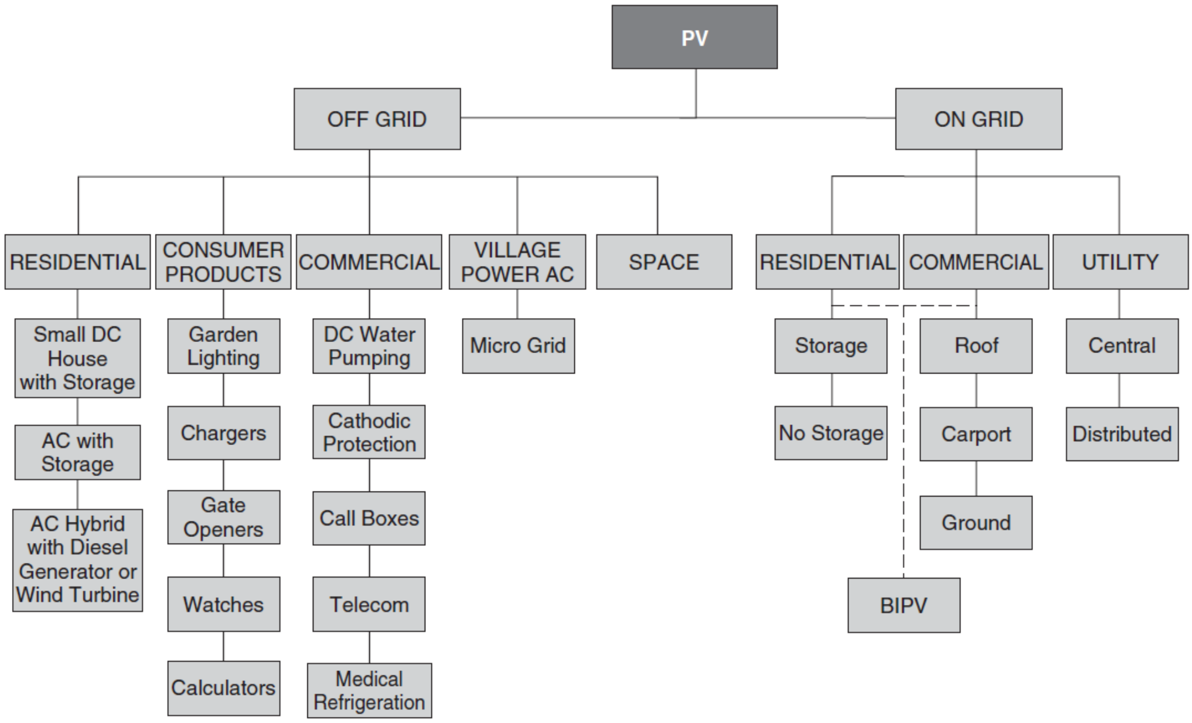


Figure 7: PV system taxonomy chart [25]

On-grid systems is less expensive per kW to install and maintain and will operate more efficiently than its off-grid counterpart. However, if no grid exists, it is usually very expensive to extend grid service into a remote area. In such cases, despite their relatively high cost and lower efficiency, off-grid PV systems are often the best solutions compared to traditional fossil-fueled generators, regular battery swap-outs, or foregoing electric power altogether. Similarly, all portable applications of PV provide power to non-stationary end uses.

2.7.2. BIPV

Building-integrated photovoltaics (BIPV) is the concept of integrating photovoltaic element into the building celling, establishing a symbiotic relationship between the architectural design, structural and multi-functional properties of the building materials and renewable micro energy generation. Thus the PV modules replace conventional construction materials and perform the function of these materials. In principle, BIPV can be used in all parts of the building envelope, although roof surfaces are the preferred area for installing PV modules due to their advantageous irradiation values. In addition, façades and window structures also give huge potential.

BIPV offers an opportunity to make micro renewable energy generation cost competitive with conventional fossil fuels. By substituting conventional building envelope construction materials with PV modules, the additional installed cost of PV energy generation becomes negligible within the total building and in some cases cheaper on a square meter basis.

In the last three decades, there have been undergoing efforts to accelerate the deployment of electricity from PV products that are integrated with building materials. Despite these efforts and increasing stakeholder's interest in BIPV, its deployment was low compared to rack-mounted PV systems worldwide until end of 2009. The different types of PV installation for electricity generation in buildings are shown in Figure 8.

(a) Least integrated (b) More integrated

(c) Fully integrated

Figure 8: residential solar system designs PV integration (a) Open rack-mounted, (b) Close roof rack-mounted and (c) Direct-mounted BIPV, multifunctional [26]

NREL’s study of BIPV for residential rooftops [26] show that there is a big cost, performance and market driving factors to BIPV for residential rooftops. It has also reviewed history of BIPV product development and study market dynamics that have affected commercialization and deployment. The study compared the prices of three hypothetical BIPVs with the price of a rack-mounted crystalline silicon (c-Si) PV system, which is the most commonly installed technology for residential applications. One of the BIPV cases is a based on derivative of the c-Si PV case, and the other two are based on an analysis of thin-film technologies as shown in table 3.

Table 3: Cases Used to Analyze Residential Rooftop PV System Prices

Scenario	**Technology**	**Form**	**Efficiency**	**Module area(m^2)**
PV Reference Case	c-Si	Rigid	14.5%	1.28
BIPV Derivative Case	c-Si	Rigid	13.8%	0.58
BIPV Thin-film Case 1	CIGS	Rigid	11.2%	0.58
BIPV Thin-film Case 2	a-Si	Flexible	5.8%	0.58

a-Si—amorphous silicon; CIGS—Cu(In,Ga)Se2; c-Si—crystalline silicon.

Figure 9 shows the price comparison of rack mounted PV and three different BIPVs. The listed effective prices account for cost offsets because of an assumption that BIPVs replace traditional building materials. In this analysis, although BIPV are expected to reduce the price because of reduced hard wares to install them; however, module price and efficiency will really matter more on the price reduction.

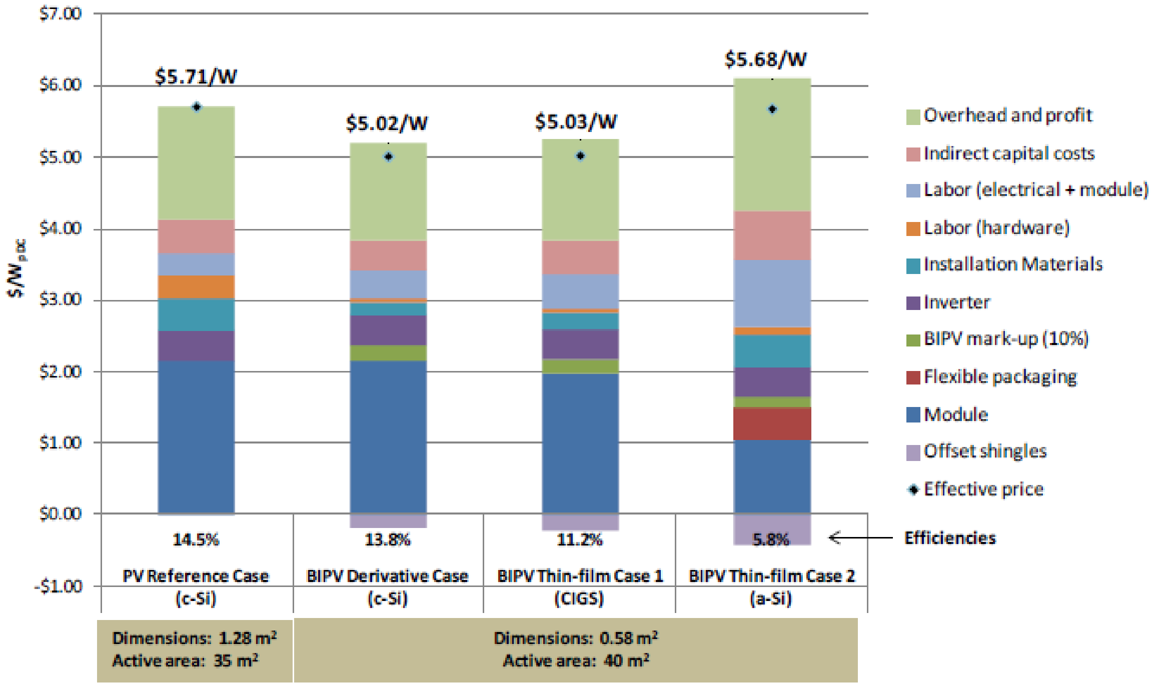


Figure 9: Comparison of residential rooftop prices for a rack-mounted PV and three BIPV cases (Listed BIPV prices include building-material cost offsets (shown as negative bars)

Table 4: Summary of silicon PV LCA results [27]

Panel type	PV system	Country	Modules efficiency	FU	Boundaries	Methodology	results
Poly.	Roof-mounted	Spain		1kWh	Production (BOS), installation and use	EPBT	EPBT 3.5–5 years
Poly. and amorphous	Roof-mounted	US	From 6.3 to 13%	1kWh	Production (BOS) and use	EPBT, CO2	EPBT: 3.15–7.4 year CO2: 34.2–72.4 g/kW h
Poly.	Roof-mounted	Several locations (EU, Austria, US)	16%	0.65 m^2 panel	Production and use	EPBT, CO2	EPBT 3,5–7 year CO2: 50–800 g/kW h
Crystalline	Tracking system	South Europe and North Africa	12.4%	1kWh	Production (BOS) and use	EPBT	EPBT <5 year
Mono.	Facade-integrated	US		1kWh	Production (BOS) and use	EPBT, IPCC (GWP)	EPBT=3.8 year GWP=10.2 g/kWh
Poly. and mono.	Roof and façade	Switzerland	From 13.2 to 14.8%	3kWh	Production (BOS) and use	Eco-Indicator 99 EPBT	EPBT=3–6 year GWP=136–100 g/kW h
Poly.	Ground-mounted	Italy	14.4%	1kWh	Production (BOS) to EoL	Eco-Indicator 99	CO2 (with Eco-Indicator):8.74 g/kWh
Poly.	Tracking system	Spain	13.1	1kWh	Production (BOS) to EoL	IPCC 2007 (GWP) EPBT Eco-Indicator 99	EPBT=1.45–1.5 years
Mono.	Building Integrated Concentrated	Spain			Production	Eco-Indicator 99 (Norm) EPS 2000 (Norm)	
Poly.	Roof-mounted	Netherlands		1kWh	Production (BOS) to EoL	Eco-Indicator 99 (Norm)	
Poly.	Ground-mounted	Germany	12.5%	1kWh	Production (BOS) and use	Eco-Indicator 99	GWP=0.063 kg/kW h
Mono.	Tracking system	Italy	13.8%	1MWh	Production and use	Eco-Indicator 99	EPBT=5.5 years GWP=44.7 g/kW h.
Poly. and mono.	Roof-mounted	South-European locations	From 11.5 to 14%	1kWh	Production and use	CML 2000	EPBT: 1.7–2.7 year CO2: 30–45 g/kW h
Crystalline			15%	1 kWh	Production	EPBT CO2 CML 2000 (Norm)	Direct CO2 Emission << indirect
Amorphous/Nano crystalline	Roof-integrated	Netherlands	10%	1kWh	Production (BOS) and use	ReCiPe EPBT	EPBT=2.3 year

FU= Functional Unit. Boundaries: (BOS): the BOS components are included in the LCA – EoL: End of Life. Methodology: (Norm): the results are only expressed after normalization – CO2==CO2 emissions calculation.

2.8. Energy supply Analysis of BIPV (household level)

Norway's building stock energy demand represents about 40% of the final energy consumption, of which 22% goes to the residential sector and 18% to the non-residential sector as shown in Figure 10. 80% of the energy for buildings comes from electricity [28].

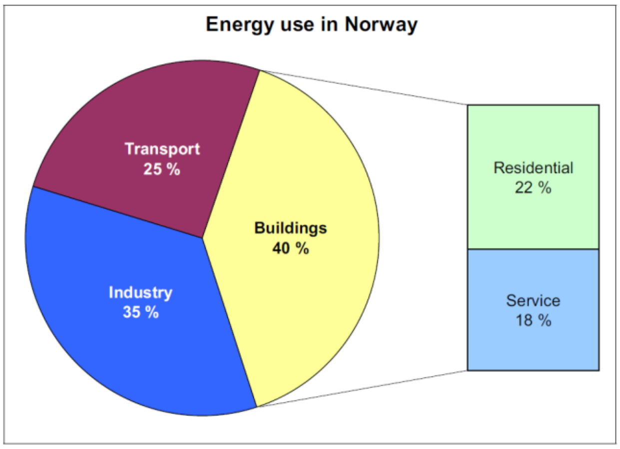


Figure 10: Final energy use in Norway in 2002, by sector [29]

The energy needed to satisfy specific end uses in a building is called net energy as shown in Figure 11. This energy includes: heating, cooling, ventilation, hot water, lighting and other electric equipment.

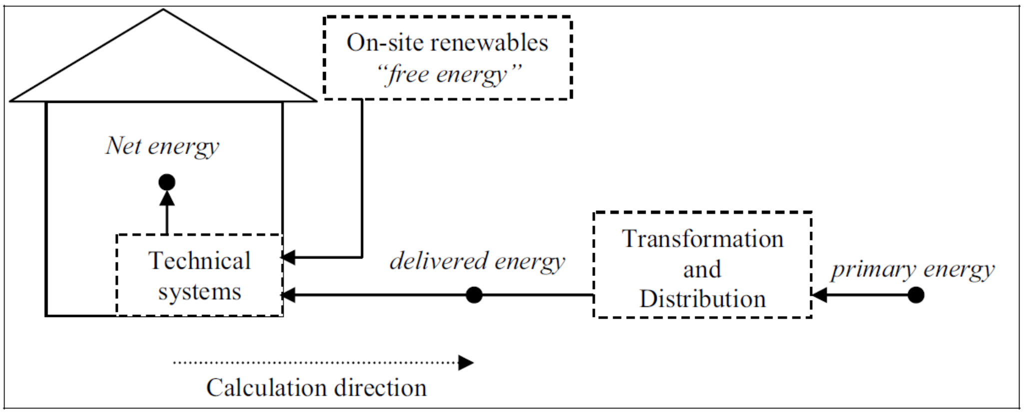


Figure 11 Delivered energy as the study object [29].

Although, electricity is the most important carrier used for heating purposes in the Norwegian building sector, however, it is often complemented by other carriers, and the actual use of electricity or alternative carriers depends on how the system runs and on price variations. The user preference to alternative energy to satisfy their heating needs is derived by combining information on delivered energy, net energy demand and system efficiencies. The values observed in the period 1996-2005 were averaged and the trend observed in the period of 1996-2005 is continued linearly until year 2035. Both average and trend values of alternative heating carriers are given in Table 5.

Table 5 User preference on carriers for heating [29]

Sector	year	Electricity direct	District heating	Wood	Gas	Oil	Heat from HP
Residential	Average 1996-2005	80.7 %	0.9 %	% 8.9	0.3 %	8.1 %	1.1 %
	Trend to 2035	61.8 %	2.7 %	18.7 % %	2.5 %	0.0 %	14.4 %

2.8.1. Annual Energy consumption of households

Before any proposal for alternative energy integration or installation it is highly recommended to know the energy consumption of appliances and understand the energy consumption behavior of households. Table 6 and table 7 gives the estimated and measure annual electric energy usage of households in Norway respectively [29].

Table 6: Estimates of annual electric energy consumption by household appliances

Appliance	Yearly measured mean consumption	Yearly measure minimum consumption	Yearly measured maximum consumption
Unit		**kwh/appliance**	
Water heater	2987	971	5570
Lighting	1000	-	-
Refrigerator without freezer	307	58	1325
Refrigerator with freezer	374	71	1028
Freezer	631	78	2120
Washing machine	209	39	978
Clothes dryer	267	49	1004
Dishwasher	206	69	693
Desktop PC	220	9	602
Laptop PC	87	11	424
Router for internet	51	34	68
Wireless access point	74	41	106
Printer	26	26	26
TV CRT	172	21	891
TV LCD	223	24	696
TV plasma	325	42	799
DVD recorder/player	21	3	37
HI-FI	103	22	240
Satellite/cable/air set top box	84	39	131
Heat pump/air conditioner	1179	601	2270
Electric cooker/oven	280	58	695
Microwave oven	30	26	33
Water kettle	24	13	36
Total	**8880**	**-**	**-**

In Norway, apart from heating, hot tap water and lighting; freezer is the most energy intensive appliance.

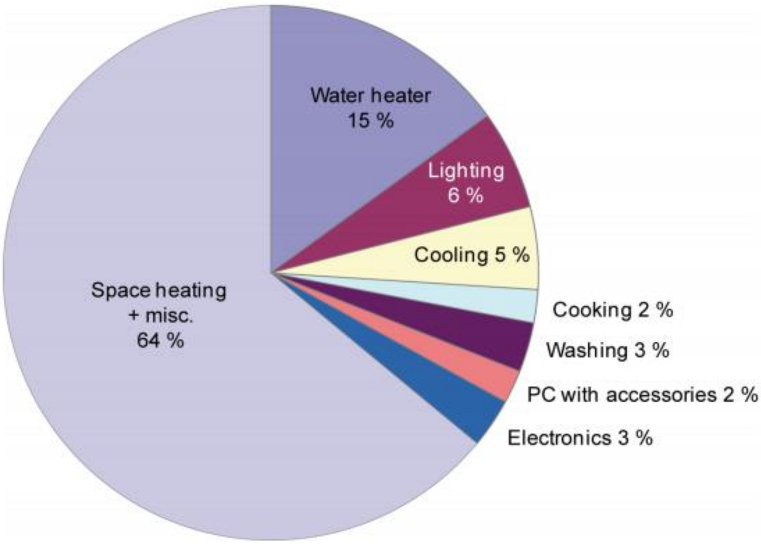


Figure 12: shares of electrical end-uses in Norway for 2006/2007 [29]

Table 7 shows measured and average energy consumption for a national average household. Therefore, the national average household energy consumption is then about 6000 kwh/year excluding space heating.

Table 7: measured annual household electric energy demand

Appliance	**Measured yearly consumption**	**Average yearly consumption**
Unit	**kwh/appliance**	
Water heater	2987	2539
Lighting	1000	1000
Refrigerator without freezer	307	160
Refrigerator with freezer	374	247
Freezer	631	461
Washing machine	209	201
Clothes dryer	267	125
Dishwasher	206	181
Desktop PC	220	154
Laptop PC	87	63
Router for internet	51	34
Wireless access point	74	19
Printer	26	16
TV CRT	172	120
TV LCD	223	112
TV plasma	325	163

DVD recorder/player	21	16
HI-FI	103	103
Satellite/cable/air set top box	84	33
Electric cooker/oven	280	269
Microwave oven	30	3
Water kettle	24	12
Total	**8880**	**-**

2.8.2. PV system design considerations and options

Generally, there are two types of electrical designs of PV power systems for homes. These are:

1. Systems that interact with utility power grid and have no battery backup and
2. Systems that interact and include battery backup

Most commonly used PV have all or many of the system components listed in Figure 13.

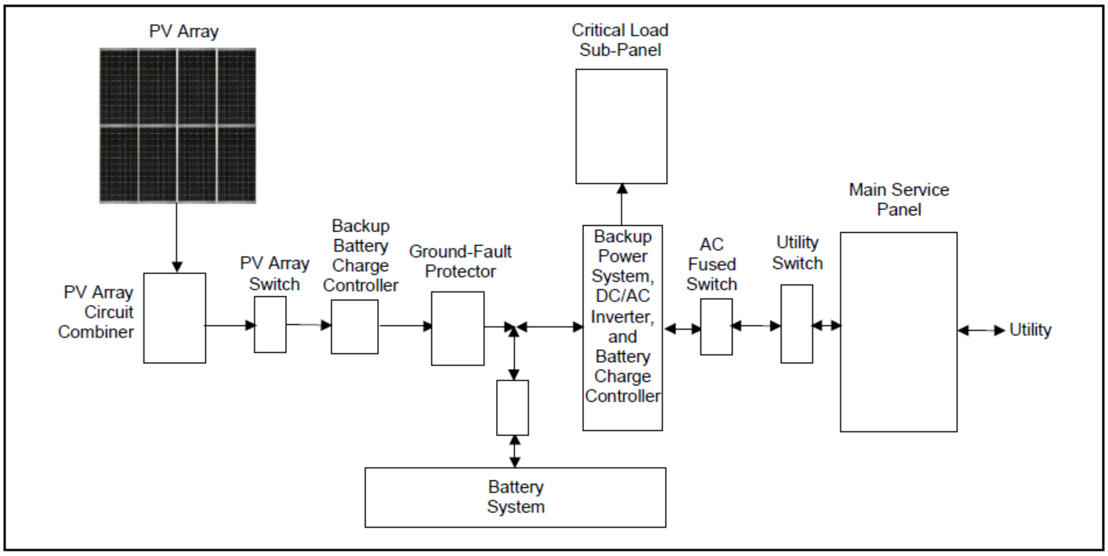


Figure 13: Components of a PV system

2.8.3. PV systems Orientation and installation

PV modules can be oriented using different techniques such seasonal tilting, use single or two axis tracking systems or BIPV such as roof tiles or shades. PV Systems with single or two axis tracking are mostly used for ground mounting and they are assumed to require more maintenance due to their mechanical parts. Such techniques are not recommended for roof PV installations. In addition, this mounting technique is expensive. Knowing the PV orientation helps to optimize the amount of radiation collected by the PV modules. Tilt angles of fixed modules can maximize the seasonal or annual performance of installed modules.

The tilt angle (β) shown in Figure 14 is defined as the angle of the highest annual irradiation and it depends on both latitude (φ) and local climate. Theoretically, the optimal orientation, surface azimuth, is true south not magnetic south and the optimal tilt is equal to the latitude of the place where the PV is installed. However, empirically, it is generally preferable to have the system facing the equator and tilted at approximately 10–15◦ less than the local latitude [25]. This is principally a consequence of poor weather being concentrated in the winter months. Other factors that influence the optimal orientation and tilt are:

1. Convenience (an existing slope is often less expensive to install upon)
2. Local obstructions (shading due to trees and surrounding buildings)
3. Asymmetrical microclimates (consistent morning fog or afternoon showers) and
4. Sensitivity to time-of-delivery generation

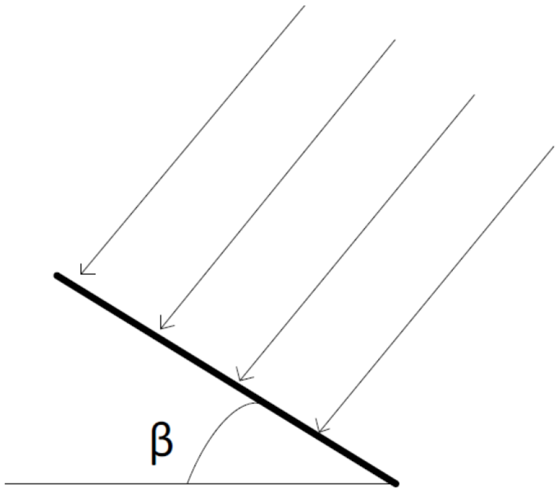


Figure 14: Tilt angle β [30]

$$\beta opt = 3.7 + 0.69 \mid \varphi \mid \quad (3.2.1)$$

It is argued that latitudes less than 65◦ can have a 0.9φ optimal tilt angle for optimum annual performance of installed PV systems [31, 32]. Though, the rule of thumb, optimum tilt angle is equal to latitude angle, works for nearly all regions in the world [33], larger deviations are given for regions of latitude higher than 45◦ N or lower than 45◦ S. This is due to more clouds, therefore more diffuse irradiation can be best captured by flat tilted modules.

2.8.4. Estimating BIPV System Output power

The power obtained from PV systems is proportion to the intensity of sunlight striking the solar array surface. The intensity of solar light on the array surface varies throughout a day and from day to day, therefore the actual output power of the system has an intermittent nature. In addition to the light intensity, there are other factors that affect the output power PV systems. These factors include:

a. Standard Test Conditions (STC):

Solar modules produce dc electricity. Manufacturers rate the dc output of solar modules under STC. These conditions are solar cell temperature of 25ºC, solar intensity of 1000 W/m^2, and solar spectrum. Although manufacturer usually rate the output of their solar modules, these modules often produce with a tolerance of +/-5% of the rating.

b. ***Temperature***

PV module output power reduces as module temperature increases. Crystalline modules usually have a typical temperature reduction factor recommended of 89% or 0.89. Therefore, which means a 100-watt module is typically operating at about 85 Watts (95 Watts x 0.89 = 85 Watts).

c. Dirt and dust

Dirt and dust can block some of the sunlight and reduce output. Considering some dust build up on a solar modules, many used annual dust reduction factor of 93% or 0.93 to calculate the total power output of an array. For example, a 100 watt module operating with some accumulated dust may give an average power of 79 Watts (85 Watts x 0.93 = 79 Watts).

d. Mismatch and wiring losses

PV arrays always have smaller maximum power output compared to the sum of the maximum output of individual modules. This difference comes as a result of sunlight inconsistence in performance from one module to the other and is called module mismatch. Mismatch accounts for at least a 2% loss in the total module power. In addition, power is lost due to resistance of system wiring. These losses are considered below 3% of the total power output.

e. Dc to ac conversion losses

Inverter is used to convert the dc power generated by the solar module into ac power. Some power is lost in the conversion process and wiring from the array to the inverter and out to the house panel. Modern inverters commonly used in residential PV power applications have peak rated efficiencies of 92-94%. The actual dc-to-ac conversion efficiency is about 88-92%. Therefore, a 100-watt module output affected by production tolerance, heat, dust, wiring, ac conversion, and other loss factors will convert into about 68 Watts of AC power delivered to the house panel during the middle of a clear day (100 Watts x 0.95 x 0.89 x 0.93 x 0.95 x 0.90 = 67 Watts).

3. Methodology

3.1. Industrial ecology

Industrial Ecology is a multidisciplinary of engineering and social science designed to understand the use and transformation of resources and the production of pollution and waste in the process of creating prosperity. It assesses technologies, political incentives and environmental standards, and also shape the physical economy and the societal metabolism. The field increases the knowledge base on the impact of modern lifestyle on our environment and on how this lifestyle can become more sustainable.

3.2. 3.2. LCA of Net ZEBs

Life cycle assessment (LCA) aims at comparing and analyzing the potential environmental impacts of a given products and services at every stage of their life. The ISO 14040 and 14044 standards provide general guidance to perform LCA through the following four interdependent stages [27]:

a. Goal and scope definition
b. Life Cycle Inventory (LCI)
c. Impacts assessment, and
d. Results interpretation.

Figure 15 presents the frame work of LCA

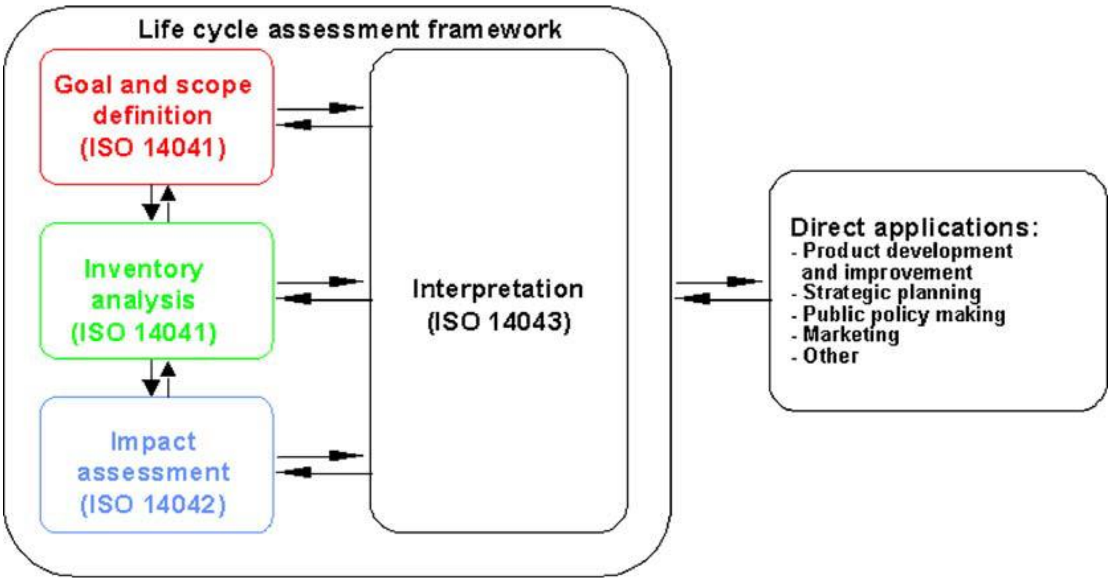


Figure 15: Life cycle assessment framework [27]

a. Goal and scope definition

Goal and scope definition is the first step to conduct LCA. The goal of an LCA includes the intended application, reasons for conducting the study, and the audience. Goals could include gaining a better understanding of an existing system, identifying the main environmental problems in the product or process life cycle, identifying opportunities for improving the existing system, comparing systems and their potential impacts, and selecting options respectively.

The scope of LCA identifies the product system or process to be studied, the functions of the system, the functional unit, system boundaries, allocation procedures, impact categories, data requirements, assumptions limitations, and type and format of the final report. The following explanations help to define/understand the scope well:

- Product system: defines the product in terms of its function. A product system consists of a set of unit processes that are linked to one another by flows of intermediate products or waste. These flows include resources used and releases to environment. Dividing the product system into its component unit processes helps in the identification of the inputs and outputs of the product system.

- Functional unit: provides a quantitative reference to which inputs and outputs are related.

- System boundaries: are formulated based on the scope of the LCA, and an initial collection of data. The description of a product system and its boundaries affect the quality of the life-cycle inventory (LCI) and its life-cycle impact assessment (LCIA). The system boundaries may defined as:

    - Boundaries between the system and the environment. These identify the types of environmental and economic processes that are included or excluded.
    - Boundaries between the system under study and one or more other related systems. These boundaries define how the environmental load is allocated in a “multifunctional process.”
    - Boundaries between relevant and irrelevant processes. This type of boundary addresses the removal of processes from the analysis. Processes can be removed (or cut off) for two reasons:

- For simplicity
- Lack of (accessible) data;

- Impact categories refer to the types of environmental impacts to be considered. Most LCAs include resource use, global warming, acidification, and others. The selection of impact categories will determine the types of data that will need to be collected.

- Data requirements depend on the level of detail of the study and the need for site-specific or generic data.

b. Life Cycle Inventory (LCI)

LCI is a phase where data are collected to quantify the inputs and outputs of the system to meet the goals of the defined study. The types of data include energy, raw materials, and other physical input; products, co-products, and wastes; releases to air, water, and soil; and other environmental aspects. Generally, a flow model (or flow chart), consistent with the system boundaries defined in the goal scope and definitions is constructed. The flow model shows the activities in the system (e.g., processes, transportation, waste management etc.) and the input and output flows among them throughout the life cycle. Calculations are then performed to estimate the total amounts of resources used and pollution emissions in relation to the functional unit. The results consist of an inventory of the environmental input and output data of the system being studied. Data can be presented in tabular or graphic form. An LCI will usually record all of the inventory results, but will typically focus on a subset of the total.

c. Life cycle Impacts assessment

LCIA assesses the results of the LCI (quantified input/output) to understand their environmental significance. LCIA is used to translate or convert inventory results obtained from the LCI into consequences.

d. Results interpretation

The LCI and the LCIA provide data about environmental releases and impacts. To use these results for process, product, or design changes, or for other purposes, decision makers need an understanding of the reliability and validity of the information. Analyses to assess the robustness of the results and conclusions, which includes the following:

- Sensitivity analyses identify and check the effect of critical data on the results. It can be conducted by systemically changing the input parameters. Input parameters for which only a small change leads to a major change in results would be identified as the most critical and those for which accurate data are most important.

- Uncertainty analyses check the effect of uncertain data (e.g., data that are estimated or approximated). Uncertain data occurs when the environmental performance of different suppliers varies under different conditions produce different emissions. To determine the effect of uncertain data, the varying data must be collected and evaluated to examine their range and distribution.

- Variation analyses assess the effects of alternative scenarios and life-cycle models. For example, if the same processes are used in two different countries with different energy sources, the life-cycle results could be different. Also, by changing chemicals used in a process or the materials used in various types of equipment, users can identify and evaluate which changes have significant impacts on the results and which produce only small changes.

Other analyses conducted in the interpretation phase that help to evaluate results include the following:

- A contribution analysis identifies the environmental loads that contribute most to the total environmental impact. Once the impacts have been characterized in the LCIA, the contributions of the various emissions can be identified and compared. Thus a certain inventory item is traced back to the share for which the different unit processes are responsible. Typically, the results are presented as percentages of the total for each emission in the process's environmental profile.

- A dominance analysis identifies the parts of the life cycle that cause the greatest environmental impact. In a dominance analysis, the emissions or environmental impact of each activity in the life cycle are examined. A dominance analysis can show areas or processes in which improvements are most needed or desired. The dominance analysis can also help identify relatively benign activities, which may be important in debates over what production processes cause the greatest environmental concerns. Activities can be grouped together so that a dominance analysis can compare impacts (or inventory results) for aggregated phases such as production, transport, use, and waste management.

- A breakeven analysis is used to investigate trade-offs pertaining to the use of products. For example, energy use associated with different containers (e.g., single-use versus multiple-use containers) can be compared. Here, the intent would be to determine the number of times that a multiple-use container must be used before the energy consumed in its more complex production process (and in its washing between uses, if necessary), equals that of the more simple-to-produce (and therefore presumably less environmentally damaging) container that is used only once. Breakeven analyses can also be used to compare materials over their life cycles. For example, aluminum, steel, and plastic tankers could be compared over their life cycles to identify breakeven points. In such comparisons, manufacturing processes, recycling options, and energy consumption during the use phase would be compared with the weight of each tanker and recycling options considered for each material.

- A perturbation analysis identifies parameters for which a small change induces a large change in a selected result. The factor that relates a small change in input to a change in output is known as the multiplier. Multipliers larger than 1 or smaller than −1 indicate sensitive parameters; multipliers close to 0 indicate insensitive parameters.

- A comparative analysis. A comparative analysis is a systematic, simultaneous listing of the LCA results for different alternatives. A comparative analysis can be used, for example, to compare CO2 emissions corresponding to a functional unit of 1 terra joule of electricity in several countries, each having its own alternative national electricity scenarios [34].

This study has quantified and analyzed the energy and Green House Gas emissions of electricity generation from a solar PV panels. The life time of the PV facility is expected to be at an average of 25 years. The major inputs in a product's life cycle chain are raw materials and energy, and the outputs include main products and wastes. The analysis has conducted following a step by step methods of LCA started by defining goal and scope, inventory analysis, impact assessment and interpretation.

3.2.1. Goals and Scope of study

The goal of LCA in this study is to assess the energy and environmental performance of mono-si and poly-si solar modules in two different cases. One is manufacturing polycrystalline silicon cells in the Abakus PV manufacturing company, and the other is producing amorphous silicon cells from Uni-solar in the SRS energy manufacturing company. Both of them have a strong PV manufacturing base.

3.2.2. System Boundary

The system boundary of LCA for the selected PVs products is ' Cradle to Gate' and is defined in a simplified flow chart along the functional unit, where all the material requirements including energy, material inputs, PV production and transportation of the raw materials and the final PV products. The flow chart and system boundaries of selected PVs are given in Figure 16 and Figure 17.

3.2.3. Functional Unit and Geographical Scope

The functional unit for LCA of PVs is defined as unit m^2 of module. Due to lack of compiled data from the manufacturing companies, the manual of U.S. Energy Information Administration (EIA) was used as a source of data.

3.2.4. Life cycle Inventory

The inventory analysis involves data collection and calculations to quantify the material, and energy inputs, out puts and emissions in the life cycle of the system. Table 2 and 3 gives the complete life cycle inventory of multi and uni-silcon PV respectively.

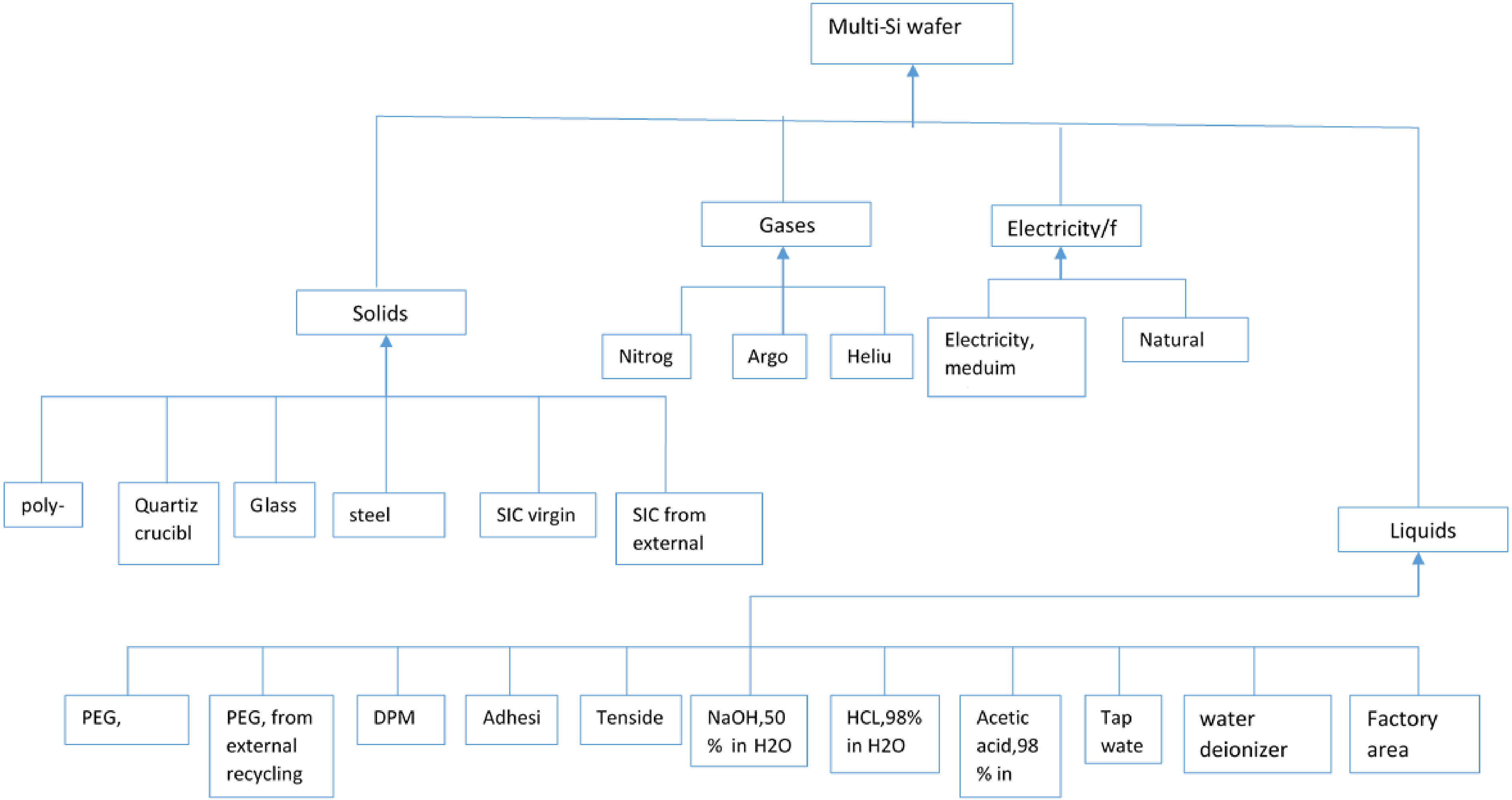


Figure 16: flowchart of Multi-si wafer

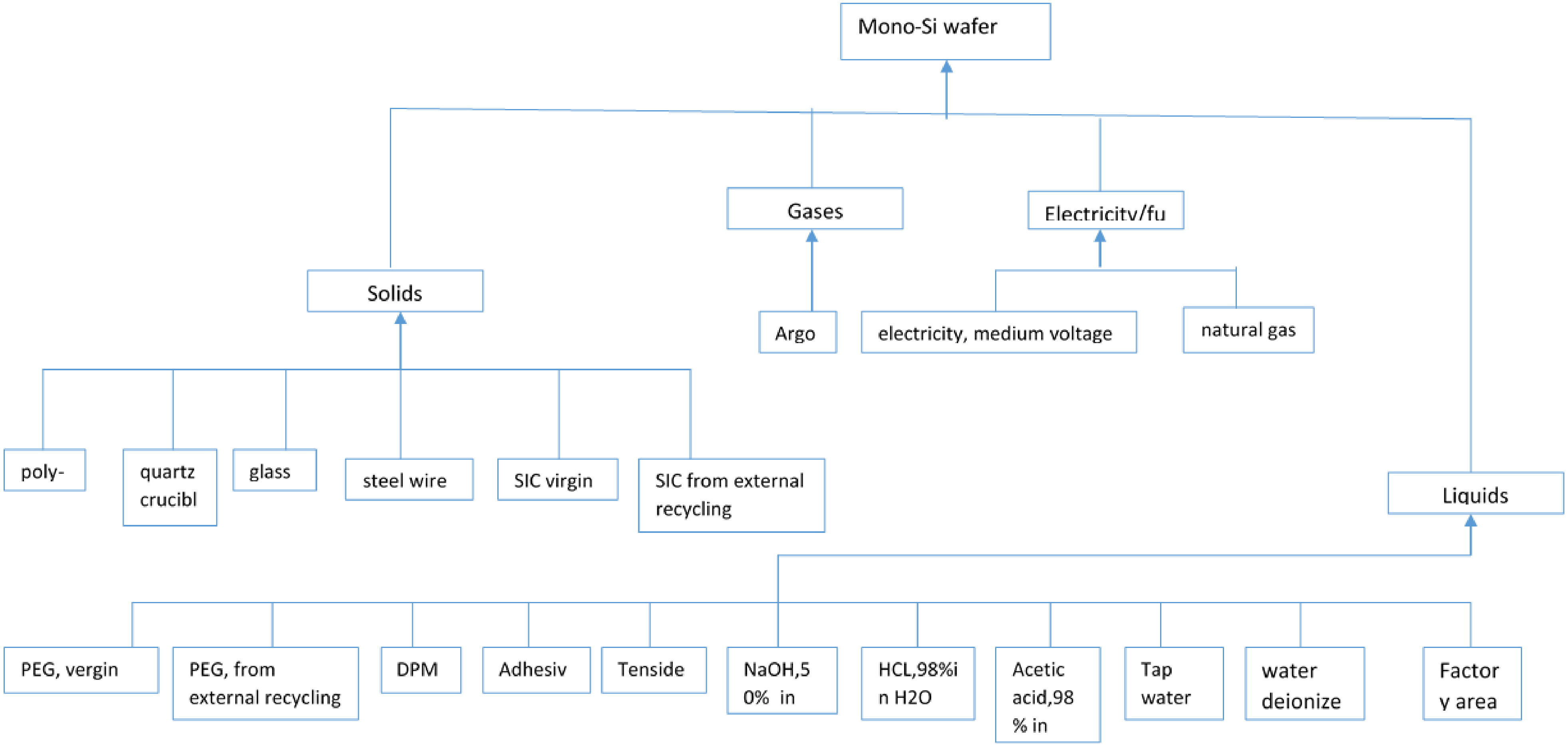


Figure 17: Flowchart of mono-si wafer

Table 8: LCI of Multi-Si Wafer [35]

Products	Unit	Amount	Comment
Multi-Si Wafer	M2	1.00	Typical wafer area: 156x156 mm2 (0.0243 m2), average thickness 240 um
Materials used			
SOLIDS			
Poly-Si	kg	1.30	Polycrystalline silicon of semiconductor or solar grade quality. This value is the total silicon needed minus internally recycled silicon from ingot cut-offs and broken wafers.
quartz crucible	kg	0.39	For ingot growing
glass	kg	0.01	For temporarily attachment of bricks to wire sawing equipment
Steel wire	kg	1.49	For wafer cutting
Silicon carbide (SIC),virgin	kg	0.49	For sawing slurry
Silicon carbide (SIC), from external recycling	kg	2.14	For sawing slurry
GASES			
Nitrogen (N2)	kg	0.05	For ingot growing
Argon (Ar)	kg	0.30	For ingot growing
Helium (He)	kg	1.362E-04	For ingot growing
LIQUIDS			
Polyethylene glycol (PEG), virgin	kg	0.11	For sawing slurry
Polyethylene glycol (PEG), form external recycling	kg	2.60	For sawing slurry
Dipropylene glycol monomethyl ether (DPM)	kg	0.30	For wafer cleaning
adhesive	kg	0.002	For temporarily attachment of bricks to wire-sawing equipment
Tenside (concentrated)	kg	0.24	For wafer cleaning
Soduim hydroxide|, 50% in H2O	Kg	0.24	For wafer cleaning
Hydrochloric acid, 30% in H2O	kg	0.0027	For wafer cleaning
Acetic acid, 98% in H2O	kg	0.039	For wafer cleaning
Tap water	kg	0.006	For ingot sawing
Water, deionizer	kg	65	For wafer cleaning
Factory area	M2	4.30E-04	2400 m2 factory producing 30 MWp/yr (9 min wafers); assuming 25 years life of factory
Electricity/fuel			
Electricity, medium voltage	kwh	30	Total electricity consumption including direct and indirect process energy and overhead energy
Natural gas	MJ	4	For removing adhesive after sawing

Table 9: LCI of mono-Si Wafer [35]

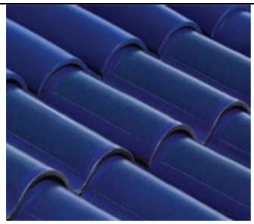
Products	Unit	Amount	Comment

Mono-Si wafer	M^2	1.00	Typical wafer area: 156x156 mm2 (0.0243 m2), semi square, thickness 270 um
Materials			
SOLIDS			
Poly-Si	kg	1.15	Polycrystalline silicon of semiconductor or solar grade quality. This value is the total silicon needed minus internally recycled silicon from ingot cut-offs and broken wafers.
quartz crucible	kg	0.36	For melting the silicon
glass	kg	0.01	For temporarily attachment of bricks to wire sawing equipment
Steel wire	kg	1.49	For wafer cutting
Silicon carbide (SIC),virgin	kg	2.14	For sawing slurry
Silicon carbide (SIC), from external recycling	kg	0.00	For sawing slurry
GASES			
Argon (Ar)	kg	6.20	For crystal growing
LIQUIDS			
Polyethylene glycol (PEG), virgin	kg	2.60	For sawing slurry
Polyethylene glycol (PEG), from external recycling	kg	0.30	
Dipropylene glycol monomethyl ether (DPM)	kg	0.30	For wafer cleaning
adhesive	kg	0.002	For temporarily attachment of bricks to wire-sawing equipment
Tenside (concentrated)	kg	0.24	For wafer cleaning
Soduim hydroxide|, 50% in H2O	Kg	0.015	For wafer cleaning
Hydrochloric acid, 30% in H2O	kg	0.0027	For wafer cleaning
Acetic acid, 98% in H2O	kg	0.039	For wafer cleaning
Tap water	kg	0.006	For ingot sawing
Water, deionizer	kg	65	For wafer cleaning
Factory area	M^2	4.30E-04	2400 m2 factory producing 30 MWp/yr (9 min wafers); assuming 25 years life of factory
Electricity/fuel			

Electricity, medium voltage	kWh	100	Total electricity consumption including direct and indirect process energy and overhead energy
Natural gas	MJ	77	General use + furnaces
Final waste flows			
Silicon waste (not recycled)	kg	0.11	Unused part of crystal, estimate
Waste to treatment			
Graphite crucibles	kg	0.36	
Steel wire	kg	1.49	
Waste slurry, to external recycling	kg	5.54	Waste slurry containing SiC, PEG, silicon kerf loss and iron from wire; see worksheet " slurry recycling" for treatment

The material inventories for the LCI were compiled using SimaPro. The main materials and energy usage of the two PV modules manufactured in both companies are given in table 8 and table 9. The detailed materials list was adapted from the EIA manual. Unlike the other energy sources, the operation and demolition phase shows less material flow. Therefore, in this study only the construction phase is considered with regard to material flow and the expected environmental impact. Table 10 gives list of selected PV material and type used for the analysis of this thesis.

Table 10: Literature data for building integrated photovoltaic tile products [6].

Manufacturer	Illustration	product	Test	ŋ (%)	UOC (V)	ISC (A)	Pmax (W)	FF	Area (mm x mm)	Pmax/area (W/m2)	Further information
SRS Energy Corporate Headquarters, 2400 Market Street, Suite Five, Philadelphia, Pennsylvania 19103, USA; T.: 1267 515 5895; www.srsenergy.com		Sole´ Powertile			6.3	4.6	15.75	0.54	868_457.2_76.2	39.7	39.7 Amorphou ssilicon cells from Uni- Solar , http:// www. srsenergy. com/ maint/ fil es/ SPT16% 20Techni cal% 20Specifica tions% 20090310. pdf [05.10.2010]
Abakus SolarAG Leithestraße 39 D- 45886 Gelsenkirchen Germany; www.abakus-solar. de	 	Peak On P220- 60	STC	13.2	36.77	8.22	220	0.73a	1667_1000_40	132.0	Polycrystalline silicon cells, IEC 61215 Ed. 2, IEC 61730, http:// www. abakussolar. com/ en/ pv/ modulescomponents/ products/ modules. html [16.01.2012]
		Peak On P220- 60	NOCT	12.73	33.93	6.65	158	0.70a	1667_1000_40	94.8	
		Peak On P235- 60	STC	14.6	37.21	8.48	235	0.74a	1630_1000_40	144.2	
		Peak On P235- 60	NOCT	13.93	34.44	6.86	172.5	0.73a	1630_1000_40	105.8	
		ANT P6- 60- 230	STC	14- 07	36.77	8.42	230	0.74a	1658_986_50	140.7	
		ANT P6- 60- 230	NOCT	13.57	33.91	6.93	170	0.72a	1658_986_50	104.0	

4. Results and discussion

4.1. Impacts assessment of BIPV

4.1.1. Comparison of mono and multi silicon wafer PVs

The impact categories of the two PV types given in table 11 have only indicate the pollution that has been raised in the production process of Mono and Polly silicon wafers for a given unit square meter. Table 11 has further show mono-si wafer has greater impact as compared to the multi -Si wafer. In this analysis, unlike the other impact categories climate change has registered the highest impact category in both pv types with 113 kg of CO_2 equivalent in multi silicon wafer and 169 kg of CO_2 equivalent in mono-silicon wafer. Fossil depletion and Human toxicity took the second and third most impact categories. Fossil depletion has resulted 35 and 53 kg of oil equivalent for Multi and Mono silicon wafers respectively. Similarly Human toxicity has registered 22 and 29 of 1,4-DB equivalent for Multi and Mono silicon wafers respectively. On the other hand, terrestrial ecotoxicity, marine eutrophication and natural land transformation have shown negligible environmental impact in the production of both PVs. Generally, the applied material input types have influenced the final results of the impact categories. In this regard, silicon is the most influential material input that causes the environmental impact in the multi-silicon wafer and silicon carbide is the most influential material input that causes the environmental impact of mono-si wafer. In addition, silicon carbide is the dominant one in creating pollution in Mono-si wafer.

Table 11: Selected impact categories of PV LCA analysis

Impact category	Unit	Multi-silicon wafer	Mono-silicon wafer
Climate change	kg CO2 eq	112.78	168.77
Ozone depletion	kg CFC-11 eq	0.00	0.00
Terrestrial acidification	kg SO2 eq	0.33	0.61
Freshwater eutrophication	kg P eq	0.03	0.03
Marine eutrophication	kg N eq	0.01	0.02
Human toxicity	kg 1,4-DB eq	21.71	29.09
Photochemical oxidant formation	kg NMVOC	0.28	0.41

Particulate matter formation	kg PM10 eq	0.11	0.18
Terrestrial ecotoxicity	kg 1,4-DB eq	0.01	0.01
Freshwater ecotoxicity	kg 1,4-DB eq	0.45	0.56
Marine ecotoxicity	kg 1,4-DB eq	0.47	0.59
Ionising radiation	kg U235 eq	18.66	23.66
Agricultural land occupation	m2a	2.76	2.72
Urban land occupation	m2a	0.26	0.28
Natural land transformation	m2	0.02	0.02
Water depletion	m3	0.38	0.47
Metal depletion	kg Fe eq	5.95	6.44
Fossil depletion	kg oil eq	35.20	52.85

Figure 18 shows comparison of impact categories of the two PVs. The results have shown that mono-silicon is more of depleteable compared to multi-silicon wafer. For producing a unit square meter of both PV types, climate change and fossil depletion are the first and second most pollutant impact categories respectively. Similarly, human toxicity and ionizing radiation show the same effect. However, Ozone depletion has shown the lowest impact compared to the other impact categories.

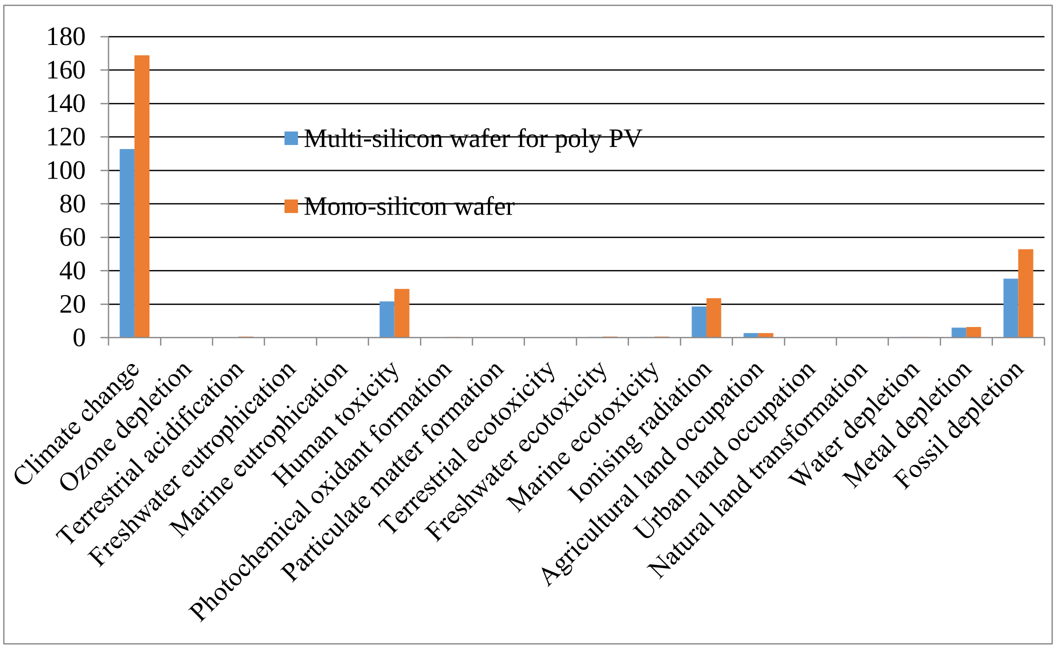


Figure 18: Impact category of Mono and Poly silicon PVs

Table 12 shows five commonly known impact categories. These impact categories are presented in Figure 20. All the five impact categories show that multi-silicon has lesser environmental impact compared to Mono-silicon wafer. Among the five impact categories, mono-si become more pollutant in climate change with a surplus 56kg CO_2 equivalent compared to Multi-si wafer. On the other hand, both PVs have similar impacts of particulate matter formation and fresh water ecotoxicity. Furthermore, the production of the two PVs have no impacts of ozone depletion.

Table 12: The five selected impact categories

Impact category	Unit	Multi-silicon wafer for poly PV	Mono-silicon wafer
Climate change	kg CO2 eq	112.78	168.77
Ozone depletion	kg CFC-11 eq	1.42E-05	1.61E-05
Human toxicity	kg 1,4-DB eq	21.71	29.09
Particulate matter formation	kg PM10 eq	0.11	0.18
Freshwater ecotoxicity	kg 1,4-DB eq	0.45	0.56

Except for the impact category of metal depletion, in almost all the listed impact categories, silicon is the most influential material input that caused environmental impacts during the production of a unit meter square of multi-silicon wafer. Steel is the most influential material input in metal depletion and the second in the impact categories of fresh water and marine ecotoxicity. In addition, it appeared in the rest of the impact categories in small amount. Electricity is the second most polluting in the impact category of terrestrial acidification, particulate matter formation, photochemical acidification, climate change and fossil depletion. Water ionization is the second polluting material in the Water depletion.

Triethlene glycol recycling, dipropylene glycol monomethyl ether have almost similar contribution in most of the impact categories. Electricity is the second polluting material in the impact categories of: Terrestrial acidification, Particulate matter formation, photochemical acidification, climate change and Fossil depletion. Triethylene glycol monomethyl ether, silicon carbide recycling and silicon carbide have negligible polluting material in almost all of the impact categories. Some input material of; Sodium hydroxide, hydrochloric acid, acetic acid, Triethylene glycol and adhesive for metals have almost negligible in polluting the environment in producing of Multi-si wafer as shown in Figure 19.

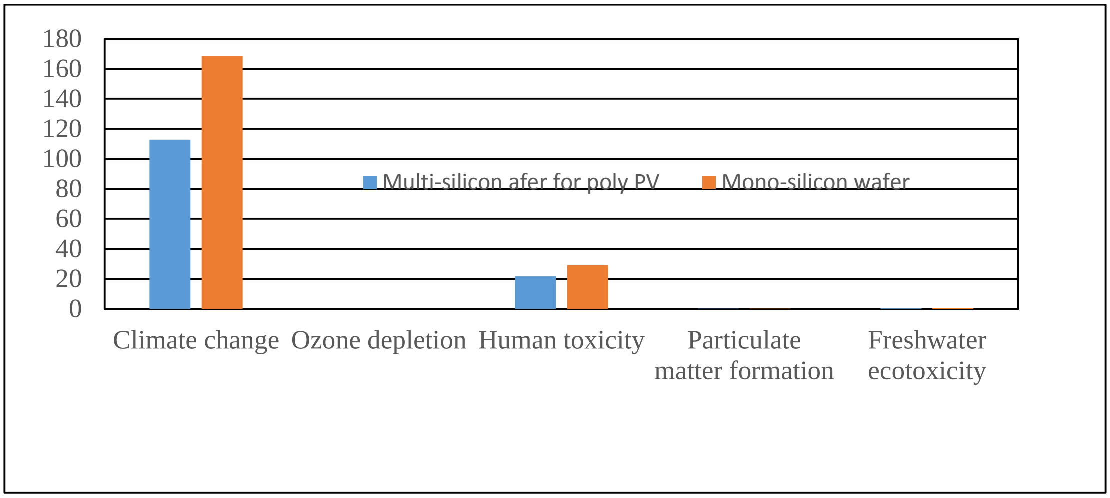


Figure 19: The five selected impact categories of Mono and Multi-si wafer

Figure 20 and Figure 21 illustrates the material inputs that used in producing a unit square meter of multi-silicon and mono-silicon wafers and their potential threats of polluting the environment. Unlike the multi-silicon wafer , in most of the impact categories: Fresh water eutrophication, human toxicity, terrestrial ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, freshwater ecotoxicity and marine ecotoxicity, silicon carbide is the most influential material input in contributing the environmental impact in producing the mono-silicon wafer. Next to silicon carbide, electricity is the second most polluting material input in creating the impact categories of climate change, terrestrial acidification, marine eutrophication, photochemical oxidation, particulate matter formation and fossil depletion. Though the impact is not much significant, dipropylene glycol monomethyl ether and natural gas do have impact in most of the impact categories. Almost half the impact category of Water depletion is caused by the material input of water deionizer. Sodium hydroxide, steel, glass, tap water, hydrochloric acid and adhesive for metals are the input material that do not have significant effect in polluting the environment.

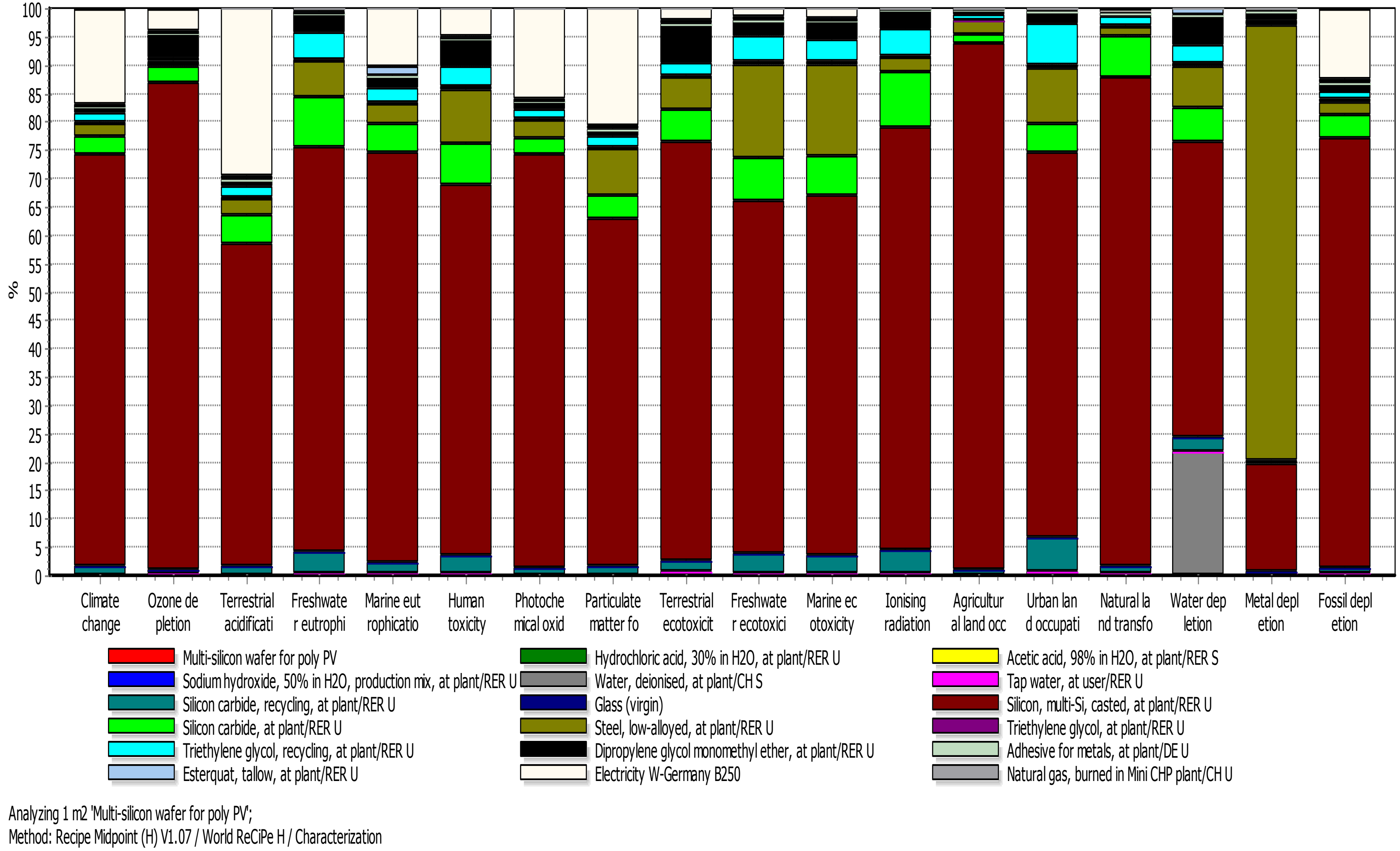


Figure 20: Analyzing a unit square meter of multi-silicon wafer PV

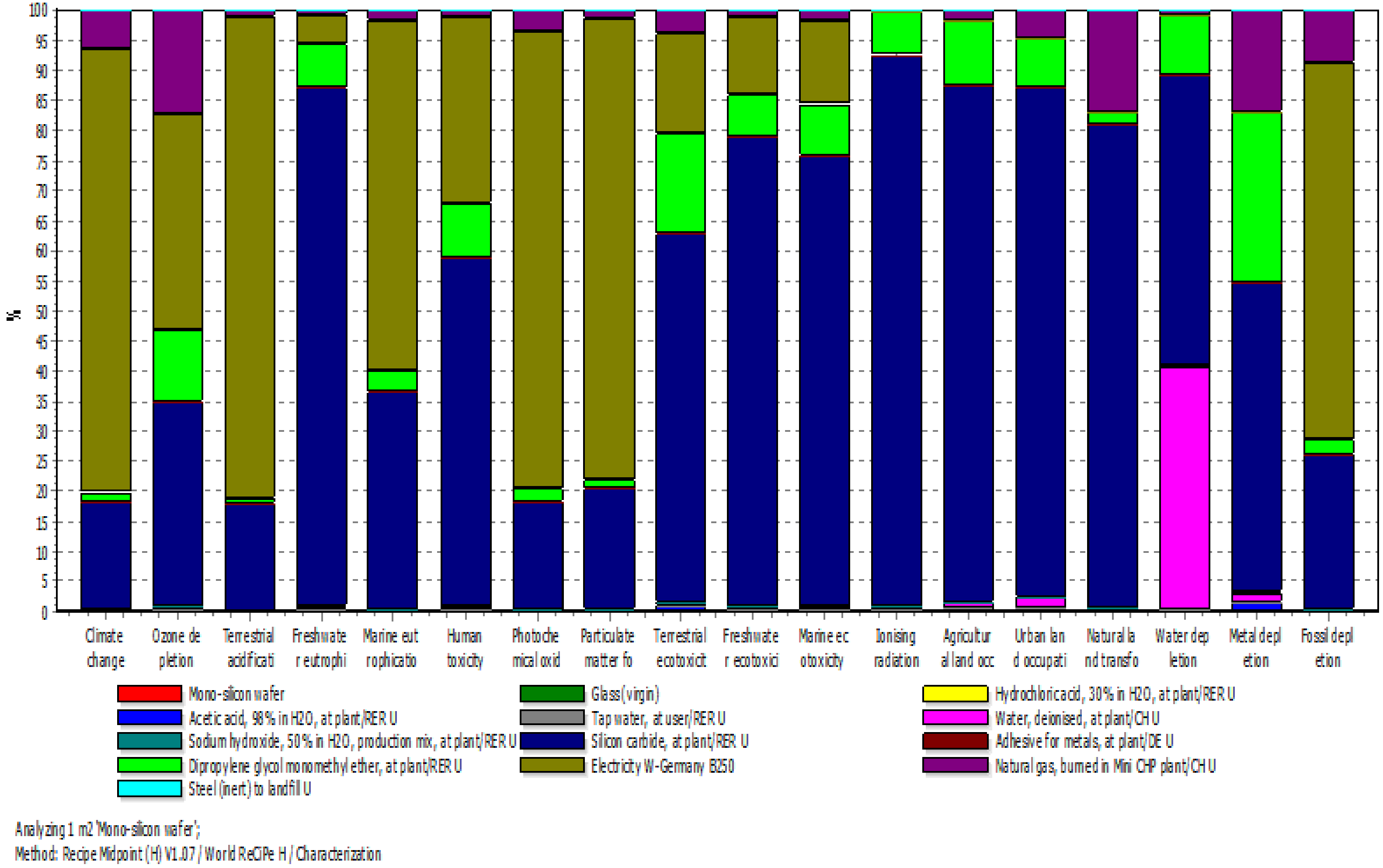


Figure 21: Analyzing a unit square meter of mono-silica wafer PV

4.2. Energy contribution of BIPV (PV sizing)

Take a building as a reference

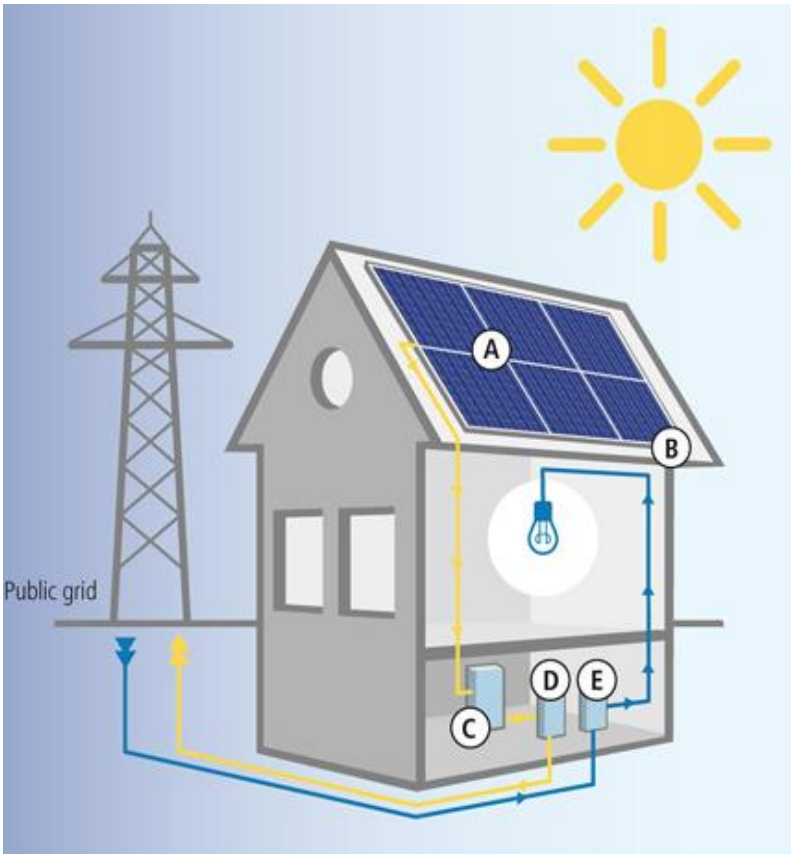


Figure 22: BIPV system and its components

Assumptions:

- Household houses with 127m^2 installed PV
- PV works for maximum of eight months per year

Table 13: Assumed house hold power consuming equipment

PV system Sizing								
No.	**loads**	**QTY.**	**watt**	**usage hours/day**	**total WH**	**total Watt**	**inverter size**	**final inverter size**
1	CFL , AC lamps	10	11	8	880.0	110	**4340**	**5425**
2	LCD TV 40" with receiver	2	220	6	2640.0	440		
3	Fridge	2	120	10	2400.0	240		
4	Tape recorder	2	50	6	600.0	100		
5	Coffee machine	2	800	2	3200.0	1600		
6	computer	3	150	6	2700.0	450		
7	Stove	1	800	6	4800.0	800		
8	Heater	1	600	2	1200.0	600		

Based on these Assumptions the following PV system sizing is calculated on excel.

Table 14: PV module selection

Total (WP)	**Solar module selection**						
	Polycrystalline Si						**Mono Si**
4420.80	**panel 1 (Peak On p220-60)**	**panel 2 (Peak On p220-60)**	**panel 3 (Peak On p235-60)**	**panel 4 (Peak On p235-60)**	**panel 5 (ANT P6-60-230)**	**panel 6 (ANT P6-60-230)**	**panel 7 (ISF-240)**
panel size in watt	220	158	235	172.5	230	170	240
qty calculated	20.09	27.98	18.81	25.63	19.22	26.00	18.42
qty rounded for 24V system	22	28	20	26	20	26	20

Table 14 shows selection of two types of PV modules, pli and mono crystalline silicon, with different module sizes.it can be observed that the polycrystalline PV module with 230W is selected for this case. This can provide the required power to electrify the households at a lower cost compared to the other PV modules.

Charge controller selection		
No of string*Isc	84.8	
with 20% safety factor	101.76	Charge controller with this spec can be selected from manufacturer

Inverter selection	
min 4975Watt @ 24V	selected inverter from manufacturer with this spec

Solar battery selection	
min 1080AH@ 2V	**Battery with this spec can be selected from manufacturer**
12 batteries required for 24V system	

5. Conclusion and Recommendation

In this study, the life cycle of Mono and Poly-Si PVs were analyzed. In addition, energy supply for a household functional unit were estimated. The direct and indirect energy requirement for producing a unit square meter of the two PV types is found to be different. It needs 100 kWh of electricity to produce Mono-Si wafer and 30 kWh for Multi-Si wafer. The environmental impact to produce a unit square meter of BIPV using multi-Si wafers are: 112.78 kg of CO_2, 1.42E-05 kg CFC-11 equivalent, 21.71 kg 1,4-DB equivalent, 0.11 kg PM10 equivalent and 0.45 kg 1,4-DB equivalent for the five common types of impact categories, Climate change, Ozone depletion, Human toxicity, Particulate matter formation and Fresh water ecotoxicity respectively. Similarly, producing a unit square meter of mono-Si wafer shows an environmental impacts of 168.77 kg CO2 equivalent, 1.61E-05 kg CFC-11 equivalent, 29.09 kg 1,4-DB equivalent, 0.18 kg PM 10 equivalent, 0.56 kg 1,4-DB equivalent correspondingly. From the electricity consumption during the production of the two PVs, in almost all the impact categories mono-Si wafer is more polluting compared multi-Si wafer.,

Furthermore, multi-Si is the influencing and sensitive material input in producing the Multi-Si wafer, i.e., a slight change in the input amount resulted a significant change in the overall result. However, tap water, triethylene glycol, and acetic acid are less sensitive in the overall results of the impact categories. Similarly, silicon carbide virgin and electricity are the most polluting and sensitive material inputs to produce mono-Si wafer. On the other hand, steel, diprophylene glycol and hydrochloric acid are less sensitive and weak material inputs.

A series life-cycle assessment analysis of BIPV of mono and multi-Si wafers has made clear that multi-Si wafer is useful as alternative source of energy because it gives less environmental impact in almost all of the impact categories compared to mono-Si wafer. It reduces a great deal of CO_2 emissions and other environmental impacts.

It was hard to get the material inputs that is used to produce both types of PVs in the web page of the PV manufacturing companies to undertake life cycle analysis of both products. This makes the study a bit difficult. Therefore, it is recommended to have a list of the life cycle inventories that is applied in producing the PVs on the web page of the manufacturers. It is also important to have further analysis on the demolition and recycling end-of-life phase of both products.

Furthermore, silicon, multi-si is the influencing and strongest material input in producing the Multi-si wafer, that is as the input amount increase or decrease there will be a great change in the overall result. However, tap water, triethylene glycol, and acetic acid do have negligible environmental impact and they are the weakest material inputs, that is as the quantities increase or decrease there is no much significant chane in the overall resultes of the impact categories. Silicon carbide virgin, and electricity are the most polluting and strongest material inputs while producing Mono-si wafer, that is a significant effect will be resulted as the amount of the these material inputs is changed. Unlikely, steel, diprophylene glycol, hydrochloric acid are the lowest influencing and weak material inputs.

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