Renewable Energy and Circular Economy: Application of Life Cycle Costing to Building Integrated Solar Energy Systems in Singapore

Rashmi Anoop Patil, Veronika Shabunko, and Seeram Ramakrishna

Abstract This chapter seeks to provide a representative example of Life Cycle Costing (LCC) for building-integrated solar energy systems in Singapore. First, renewable energy is introduced from the circular economy perspective, to better understand its significance in promoting sustainability. Solar energy among all renewable energy sources is the most promising for resource-stressed tropical cities such as Singapore. For such densely populated built-environments, innovative energy systems such as the building-integrated photovoltaic (BIPV) systems serve as good options to capture and use renewable energy incident on large facade areas. To estimate the financial feasibility of implementing BIPV systems and the cost-competitiveness in comparison with conventional building materials, the LCC serves as an enabling tool to evaluate the viability of these energy systems as per the market need. A step-by-step illustration of the LCC analysis, based on the tool developed by the BIPV Centre of Excellence at the Solar Energy Research Institute of Singapore (SERIS), is provided as a case study. This highlights the significance of LCC in evaluating the economic benefits of a practical application of a BIPV system for a representative high-rise building in Singapore. The benefits of transiting toward such sustainable and clean energy systems from a consumer and environmental perspective are summarized as the conclusion of the chapter.

Keywords Life cycle costing · Renewable energy · Building-integrated PV · Life cycle thinking · Circular economy

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Learning Objectives

- To understand and quantify the impact of renewable energy sources such as building-integrated solar energy systems for resource-stressed countries such as Singapore.
- To understand the application of LCC calculation for BIPV systems in the Singapore building sector.
- To understand the significance of LCC in transition to renewable energy sources.

1 Renewable Energy and Circular Economy

The circular economy (CE) is often understood by novices as a concept related to materials circularity and zero-waste ecosystems, with somewhat subdued focus on energy sources [1]. However, CE also emphasizes optimizing the performance of an economic system (conceptually understood as a system involving resource allocation, and production, distribution, and consumption of products and services within a given area) by consciously transiting to renewable energy (RE) such as solar, wind, hydropower, tidal, and geothermal energy, and decoupling fossil fuel utilization for energy generation [1]. The optimization of energy performance in an economic system and transition to renewable energy sources is generally a gradual process and can be realized by embracing the following modifications:

1. reducing the production and consumption of non-renewable energy sources such as crude oil, coal, and natural gas
2. improving the energy efficiency of industrial processes and electrical/electronic products
3. reducing energy wastage (due to transmission losses and/or overuse) and recycling energy generating systems (after end-of-life).

At the core of such a transition, two objectives influence the reduction in the use of fossil fuels as energy sources: (i) separating economic growth from the use of scarce resources such as fossil fuels and (ii) reducing the carbon footprint or in other words decarbonizing the current energy production and consumption. Advances in technology for energy generation and storage, evolving environmental and social consciousness, and governance initiatives such as the carbon tax are providing impetus to this transition to renewable energy sources. This development is a game-changer for the energy industry and the market, and the consumers as well.

To appreciate the role and the importance of RE in the context of the CE, its imperative to first understand the concept of RE. RE can be defined as the energy produced from sources that do not deplete over time or can be replenished within one’s lifetime [2]. Various forms of RE exist that can be harnessed using established technologies. For example, the energy in the wind currents (driven by the heat from solar energy [3]) can be captured using wind turbines. Hydropower that depends on the flow of water (another form of solar energy, as the sun powers the hydrologic cycle [4]) can also be harvested using turbine technology. The bioenergy stored in the
Renewable energy sources are derived from solar energy. Innovative technologies such as photovoltaic (PV) cells that make up solar panels can capture the incident solar energy to generate power. When all these derived energy sources are collectively considered, it is evident from a common viewpoint, that the incident solar energy is the main source of most forms of renewable energy [2].

This chapter presents a discussion on how harnessing renewable energy such as solar energy can be beneficial both financially and environmentally in the long run (Fig. 1). Such a study provides key insights into the transition dynamics involved in incorporating renewable energy systems. For the purpose of illustration, we present a real-world example of the PV technology, that has seen tremendous progress in recent years. This technology is based on the photovoltaic effect—a well-known method for generating electricity by using solar cells to convert incident sunlight into a flow of electrons (Fig. 2). The electricity generated by solar PV cells can be connected to the grid or stored using a battery. As the PV technology advanced in the recent decade, it has been possible to integrate the solar energy systems with the building facades, making the technology more feasible for the built environment.

Currently, the deployment of solar PV systems is growing globally due to the significant reduction in the production costs of PV panels. These PV deployments include both grid-tied and off-grid installations. According to the International Renewable Energy Agency (IRENA), the globally installed solar capacity had reached nearly 480 GW by the end of 2018 [5]. IRENA also estimates that solar PV power installations could grow almost six-fold over the next 10 years and reach a cumulative capacity of ~2,840 GW globally by 2030 and rise to ~8,520 GW by 2050 [5]. These projections show that in the coming decades, solar energy harnessing systems will be a major contributor to the global energy output. This transformation

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**Fig. 1** Schematic illustration of the link between circular economy, renewable energy, and LCC analysis for BIPV systems. Renewable energy as an integral part of the circular economy is first discussed followed by a case study on the capture and use of solar energy using BIPV systems and its LCC. Design adapted from a template; Copyright PresentationGO.com
will facilitate in contributing to a circular economy\(^1\) as well as the Paris Agreement requirements\(^2\) for mitigating climate change.

The discussion in the next section focuses on the transition dynamics of incorporating a solar energy system such as the building-integrated photovoltaic (BIPV) system suitable for urban built environments. The economic analysis and overall competitiveness of solar energy system are usually expressed in form of the levelized cost of electricity (LCOE). It is a well-established method to evaluate various power generation options \([7]\). The LCOE approach considers the entire lifecycle cost of a solar energy system over the duration of the project and the associated electricity generated. However, for the case of a BIPV system, the economic viability is evaluated differently, as it typically replaces conventional construction materials of the building envelope. Therefore, the cost competitiveness is evaluated against the conventional construction materials per square meter rather than the cost of conventional electricity generated, expressed in form of life cycle costing (LCC). LCC can be understood as an evaluatory study that succinctly captures the cost associated with the project (in this case, the incorporation of BIPV system) from the beginning of the project to the end of its useful life (generally, the useful lifetime of the solar panels). The LCC study includes the initial costs that include realizing the project (e.g., acquiring the solar panels and cost of installation and integration with the existing building-related energy network/grid) and operating the renewable energy system till the end of its useful life. The LCC provides a clear cost picture of the project to compare with other alternatives with respect to the long-term benefits and the impact on running costs. It can thus be understood that LCC assists in decision

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\(^1\)https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy.

\(^2\)https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.
making regarding the necessity of the project by providing critical economic analysis that compares initial investment options and assists in identifying the least cost alternatives, and economic benefits in the long run.

First, we briefly provide a background on the relevance of building-integrated solar energy systems to the urban settlements in the tropics such as Singapore and the need for its LCC for the Singapore market. An illustrative application of LCC to the BIPV system in Singapore then follows as a representative real-world case study on incorporating renewable energy systems in the built environment. The take-away message from such a study would be a basic understanding of the decision process involved in transitioning to renewable energy systems that can contribute to circularity in energy in the years to come.

### 1.1 Building-Integrated Solar Energy Systems in Singapore

Building-integrated solar energy system refers to the deployment of photovoltaic systems as a structural and/or esthetic component of the exteriors of buildings such as the facade curtain walls, cladding, windowpanes, and rooftops to cater to the energy requirements of the building without utilizing extra space [8]. Here, it should be noted that the BIPV systems installation differs from the BAPV (Building Applied Photovoltaics) type, a traditional approach of fitting modules to the existing surfaces by superimposing (such as installations on rooftops), once the construction has been completed. BIPV systems are very suitable for densely built-up cities with limited land and often competing for roof usage (e.g., with mechanical and electrical equipment such as air conditioners), but abundant solar irradiance. One such example is Singapore, which is packed with high-rise buildings and where BIPV technology could help to greatly expand the possible areas for deployment of solar PV modules (see sample installation in Fig. 3).

Currently, around 95% of Singapore’s energy requirement is sourced from imported natural gas and, hence, the country is moving towards embracing sustainable energy. In this context, transiting to a BIPV system comes with an initial financial investment but also offers environmental benefits in the long run. To facilitate such a transition, the LCC for BIPV systems provides a practical estimate of the cost-competitiveness and financial viability of BIPV technology in the Singapore market.

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3 Singapore’s Energy Story, Energy Market Authority. [https://www.ema.gov.sg/ourenergystory](https://www.ema.gov.sg/ourenergystory)
2 Case Study: Applying LCC to Singapore’s BIPV Systems

This case study\(^4\) will focus on illustrating the LCC tool application for BIPV systems considering the Singapore market and climatic conditions for evaluating the economic dimensions of this sustainable energy option [9]. A step-by-step illustration of the LCC analysis is provided below and such an analysis is suitable for consumers/real estate developers investing in BIPV systems to arrive at an economically sound decision.

2.1 LCC Parameters

Before moving to the actual calculation, there is a need to understand the different technical and financial parameters [10] involved in/influencing the LCC calculation and know their practical value range. These parameters are briefly explained and relevant values for each of them are given below.

1. **Discount Rate:** In general, the discount rate is defined as the rate of return used to discount future cash flows back to their present value. In this case, it is a part of the overall general financing cost for the real estate project. Here, the cost of BIPV facades should be included in the total cost of the real estate investment

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\(^4\)Building Integrated Photovoltaics (BIPV) Life-Cycle Cost (LCC) Calculator by Solar Energy Research Institute of Singapore (SERIS), NUS (program administrator for National Solar Repository (NSR)). Copyright 2014, SERIS. [https://www.solar-repository.sg/lcc-calculator/index.cfm](https://www.solar-repository.sg/lcc-calculator/index.cfm)
as the BIPV installation replaces the conventional construction material for the façade.

The BIPV LCC tool recommends setting a discount rate of 5% of the total real estate investment for the BIPV installation as a default number, which may be modified based on the country [9].

2. **Power/Unit area**: The power generated per unit area of a BIPV module varies with the module technology, type, transparency, and color (as the energy absorbed by the color varies). It is computed by dividing the total power (in Watts) output of the BIPV installation by the total module area (in m²) of the BIPV installation.

The BIPV LCC tool recommends the following values for different types of BIPV technologies: non-transparent black BIPV’s output is approximately 165 W/m² and other non-transparent color modules such as gray-blue, light blue, and golden provide a power output of nearly 135 W/m². The semitransparent modules provide the least power output of around 50 W/m² [9].

3. **System Price**: This includes the cost of each unit system, for instance, the BIPV module price, inverter price, cabling cost, installation fee, and framing cost in case of curtain walls.

In Singapore, a colored BIPV system per unit costs around 500 SGD (at May 2020 module cost) [11].

4. **Operating & Maintenance Cost**: Operating and maintenance cost for activities such as facade cleaning depends on the total area of the system installed and is slightly higher than the maintenance cost for conventional rooftop photovoltaic systems.

The BIPV LCC tool recommends a conservative operating and maintenance cost of 4–6 SGD/m² [11].

5. **Annual Reserve for Inverter Replacement**: This is computed based on a warranty extension cost every fifth year with escalating premiums (i.e., 25%, 40%, 60%, and so on). It is assumed that inverter cost per BIPV module power output (Wp) will reduce to around 0.07 SGD/Wp within the next 13 years and remain stable thereafter.

The BIPV LCC tool recommends to utilize a value of 5.5 SGD/kWp for annual reserve charge for inverter replacement based on assumptions in the case of Singapore: 4.8 SGD/kWp for 20 years, 5.5 SGD/kWp for 25 years, and 6.0 SGD/kWp for 30 years [9].

6. **Inflation**: The inflation rate is used to escalate operating and maintenance costs, inverter replacement cost, and residual value cost.

It is recommended to set the annual inflation rate in Singapore to be 2% for calculation purposes [9].

7. **System Lifetime**: A value for the system lifetime can be approximated based on the building’s life expectations or in-line with the output warranty of the BIPV module manufacturer.

The BIPV LCC tool recommends to set 25–30 years as the system lifetime [9].
8. **System Performance Rate:** The performance rate is an indicator of how well a solar PV system converts available sunlight into electricity. In practical applications, there are losses due to DC to AC conversion, cabling or mismatch issues, temperature effects, shading caused by nearby buildings, soiling, reflections, all of which will decrease the system performance.

   A well-designed system for Singapore’s weather conditions can achieve a performance rate of > 80%. The BIPV LCC tool recommends to consider the system performance rate to be 75% [9].

9. **System Degradation Rate:** After the first year’s specific energy yield (i.e., available irradiance multiplied by the system’s performance rate), the system degrades by a certain percentage from year to year. For temperate climates, the degradation rate is usually assumed at 0.5% and for tropical climates (such as that of Singapore), the BIPV LCC tool recommends to use a degradation rate of ∼1% [9].

10. **Residual Value:** This refers to the amount of value (in SGD) that can be recovered at the end of the system’s operational life after subtracting the dismantling and recycling costs.

    The BIPV LCC tool recommends using 0 SGD for the residual value in calculations [9].

11. **Reduced Solar Heat Gain Coefficient (SHGC):** The SHGC is a fraction of solar radiation entering through a window, door, or exterior glass walls/skylight, either transmitted directly and/or absorbed, and subsequently released as heat into the building interior. Replacement of exterior glass panels by BIPV modules that absorbs some parts of the solar radiation leads to potential energy savings as a result of cooling load reduction in air-conditioned environments which is expressed as reduced SHGC.

    The SHGC reduction can be as high as 0.4 by using glass–glass BIPV modules, or 0.2 by using see-through BIPV modules (calculation is based on a common air-conditioning coefficient of performance of 3.7).

    The reduced SHGC is considered to be 0 in conservative calculations [9].

12. **Electricity Grid Emission Factor:** The grid emission factor measures the average CO₂ emission per kWh of electricity. It is calculated using an average operating margin (OM) method which is a generation-weighted average CO₂ emission per unit net electricity generation of all generating power plants serving the system.

    Singapore’s average operating margin-based grid emission factor (OM-GEF) is 0.4188 kg CO₂/kWh in 2018 (EMA 2018). When the multi-silicon PV technology’s emission rate of 28 g is subtracted from the GEF, the updated value is 390.8 g CO₂/kWh.

13. **Carbon Tax Savings:** Carbon Tax refers to the carbon pricing of per tonne of CO₂ emissions levied by the government. Carbon Tax Savings of the BIPV system coupled with avoided CO₂ over the system’s lifetime will be estimated for LCC.

    Carbon Tax Charge (levied on consumers) = Electricity Consumed based on metered values x OM-GEF x Carbon Tax Price.
### Table 1 List of parameters’ values considered for LCC calculation

| Parameter                                      | Value                                      |
|------------------------------------------------|--------------------------------------------|
| Discount Rate                                  | 5%                                         |
| Power/Unit area                                | 135 W/m²                                   |
| System Price                                   | 500 SGD/unit                               |
| Operating & Maintenance Cost                   | 5 SGD/m² (mean)                            |
| System Lifetime                                | 25 years (lower end of the range)          |
| Annual Reserve for Inverter Replacement        | ~5.5 SGD/kWp                               |
| Inflation                                      | 2%                                         |
| System Performance Rate                        | 75%                                        |
| System Degradation Rate                        | 1%                                         |
| Electricity Grid Emission Factor               | 390.8 g CO₂/kWh (EMA 2018)                |
| Electricity Arrangement                        | NCC                                        |
| Carbon Tax Price                               | 5 SGD/tCO₂                                 |

The BIPV LCC tool recommends to set carbon tax price to 5 SGD/tCO₂ as per Singapore regulations in 2019 [9].

14. **Energy Economics:** The electricity price payable to the utility provider (in SGD cents/kWh) for either the non-contestable client (NCC) or contestable client (CC) is decided based on the average values of the respective customer group with future electricity price progression. Hence, opting to be CC, buying from a sustainable source and adopting BIPV options is more economical and environmentally friendly in Singapore.

The parameter values considered for the step-by-step LCC calculation in the following section are listed in Table 1.

## 2.2 Step-by-Step LCC Calculation for BIPV System

Let us consider a building in Singapore with BIPV system deployed on the east exterior wall/facade, spread over an area of 500 m² as shown in Fig. 4.

1. **Calculating the total initial investment**
   The total area of the BIPV system installed (east facade) = 500 m² (i).
   System price for unit area (per m²) = 500 SGD (ii).
   Therefore, the total initial investment is given by
   \[ \text{Total Initial Investment} = (i) \times (ii). \]
   \[ = 500 \times 500. \]
   \[ = 250,000 \text{ SGD}. \]
2. Calculating the total operating and maintenance (O&M) cost for the BIPV system’s lifetime

System lifetime ($N$) = 25 years.
The annual average operating and maintenance cost per unit area ($m^2$) of the system = 5 SGD (iii).
Discount rate ($r$) = 5% (or 0.05).
Inflation rate (in Singapore) ($i$) = 2% (or 0.02).

The annual average operating and maintenance cost of the BIPV system is given by
$$= (i) \times (iii).$$
$$= 500 \times 5.$$  
$$= 2500 \text{ SGD}(O&M)_{\text{initial}}.$$

The total operating and maintenance cost of the BIPV system over its lifetime is given by
$$(O&M)_{\text{Total}} = (O&M)_{\text{initial}} \times \sum_{n=1}^{N} \left(1+i\right)^{n}$$
where $N$ is the system’s lifetime,
i is the inflation rate, and.
r is the discount rate.

Substituting the corresponding values in the above equation,
$$(O&M)_{\text{Total}} = 2500 \times \sum_{n=1}^{25} \left(1+0.02\right)^{n}$$
$$(O&M)_{\text{Total}} = 2500 \times \sum_{n=1}^{25} \left(0.9714\right)^{n}$$
= 2500 x (0.9714 + (0.9714)^2 + \cdots + (0.9714)^{25}). \\
= 2381 + 2313 + \cdots + 1187. \\
= 42,960 SGD.

3. **Calculating the total inverter replacement reserve \(((\text{IRR})_{\text{Total}})\) for the BIPV system’s lifetime**

**Calculating Installed Capacity:**

The power generated per unit area of the BIPV system (non-transparent colored module) = 135 W/m² (iv).

The installed capacity of the BIPV system for an area of 500 m² is given by

= (iv) \times 500.

= 135 \times 500.

= 67.5 kW_p (v).

**Calculating the Inverter Replacement Reserve:**

The annual inverter replacement reserve per kW_p = 5.5 SGD.

The annual inverter replacement reserve for the installed capacity is given by

= 5.5 \times 67.5

= 371.25 SGD\((\text{IRR})_{\text{initial}}\).

The annual discounted inverter replacement reserve for the installed capacity, \((\text{IRR})_{\text{discounted}}\), is given by

\[
\frac{371.25}{1 + r} = 354 \text{ SGD}
\]

The inverter replacement reserve for the BIPV system over its lifetime is given by

\((\text{IRR})_{\text{Total}} = (\text{IRR})_{\text{discounted}} \times \sum^N\).

where \(N\) is the system’s lifetime,

\(i\) is the inflation rate, and,

\(r\) is the discount rate.

Substituting the corresponding values in the above equation,

\[
(\text{IRR})_{\text{Total}} = 354 \times (1 + 0.02) \frac{1}{1 + 0.05}^{n-1}
\]

\[
= 354 x (1 + 0.9714 + (0.9714)^2 + \cdots + (0.9714)^{24}).
\]

= 354 + 343 + 334 + \cdots + 176.

= 6,380 SGD.
4. Calculating the benefit of electricity production over the BIPV system’s lifetime

**Calculating the total green energy produced by the BIPV system**

The BIPV system degradation rate (SDR) = 1% (or 0.01).
Energy generated by the system in the first year is calculated to be 41,272 kWh \( (E_{\text{initial}}) \).
Total green energy produced over the system’s lifetime is given by
\[
E_{\text{Total}} = E_{\text{initial}} \times \sum_{n=1}^{N} (1 - SDR)^{n-1}
\]
Substituting the corresponding values in the above equation,
\[
E_{\text{Total}} = 41,272 \times \sum_{n=1}^{25} (1 - 0.01)^{n-1}
\]
\[= 41,272 \times (1 + 0.99 + (0.99)^2 + + (0.99)^{24}).
\]
\[= 41,272 + 40,859 + 40,451 + \ldots + 32,427.
\]
\[= 916,976 \text{ kWh}(vi).
\]

**Calculating the total electricity produced by the BIPV system**

The BIPV system performance rate = 75% (or 0.75).
So, the total electricity produced over the system’s lifetime is given by
\[= (vi) \times 0.75.
\]
\[= 916,976 \times 0.75.
\]
\[= 687,732 \text{ kWh}(vii).
\]

**Calculating the economic benefit due to the total electricity output**

The per unit of electricity tariff in July 2019 was 24.2 cents in Singapore and is considered here for evaluation.
Therefore, the electricity benefit is given by,
\[= (vii) \times 0.242.
\]
\[= 687,732 \times 0.242.
\]
\[= 166,431 \text{ SGD}.
\]

5. Calculating the total LCC for the BIPV system

As shown in Table 2, the total LCC for the BIPV system is calculated by adding up the expenditures (inclusive of the total initial investment, the total operating and maintenance costs and the total inverter replacement reserve), and subtracting the economic benefit obtained by the total power produced by the installed modules.

6. Calculating the LCC for the BIPV system per unit area

Total LCC = 132,909 SGD.
Therefore, the LCC for the BIPV system per unit area is given by
\[= 132,909 / (i).
\]
\[= 132,909/500.
\]
\[= 266 \text{ SGD}/m^2.
\]
| Item description                          | Cost (SGD) |
|------------------------------------------|------------|
| Total initial investment                 | 250,000    |
| Total Operating and Maintenance Cost     | 42,960     |
| Inverter Replacement Reserve            | 6,380      |
| Benefit from electricity production      | −166,431   |
| **Total Life Cycle Cost**                | **132,909**|

7. **Environmental benefit—Calculating the Carbon Tax savings over the BIPV system’s lifetime**

Electricity Grid Emission Factor = 390.8 g $CO_2$/kWh.

$CO_2$ savings for the system’s lifetime is given by

\[ = (vi) \times 390.8 \]
\[ = 916,976 \times 390.8 \]
\[ = 358.35 \text{ tonnes}. \]

Carbon Tax Price in Singapore = 5 SGD/t$CO_2$.

The Carbon Tax savings over the BIPV system’s lifetime is given by

\[ = 358.35 \times 5. \]
\[ = 1791.75 \text{ SGD}. \]

It should be noted that this representative example of LCC is provided here for a basic understanding of the underlying cost calculations that generally determine the economic feasibility of a BIPV system over its lifetime. A similar set of calculations is modeled as a three-step process where the user can input custom values for the parameters to assess the economic viability of the selected BIPV system. This model is presented as a user-friendly tool by SERIS on the National Solar Repository (NSR) website at [https://www.solar-repository.sg/lcc-calculator](https://www.solar-repository.sg/lcc-calculator) and is useful to further explore the effect of various parameters on the LCC values.

### 2.3 Decision Making Using LCC Analysis

Decisions about transiting to new energy systems typically involve a certain degree of uncertainty about their initial and running costs, and potential savings and energy benefits over long run. LCC greatly increases the likelihood of initiating a new project or integrating a new system that is economically feasible in the long run. Yet, there are hidden challenges associated with the LCC model and results. LCC studies are usually performed for a new project in the initial stages when only financial estimates are available and extrapolations are generally made to fill up the gap in the estimates that may be due in the years to come. This uncertainty in critical input values such as costs and savings means that the LCC outcomes may differ from the
actual outcome and occasionally this difference may be significant. There are, in
general, two approaches to address this concern.

(i) Sensitivity analysis: A technique generally recommended for energy and water
projects, sensitivity analysis is useful for identifying which of several uncertain
input values has the most significant impact on the economic evaluation of the
project. It also provides an estimate of how variability in the input values affects
the economic evaluation of the project.

(ii) Break-even analysis: Decision-makers such as project builders, consumers, or
real estate developers, many a time, want to know what minimum benefit a
project can yield over the long run, say few years or a decade, and still, cover
the cost of the investment.

A detailed description of these analyses is beyond the scope of this chapter.
However, the reader should appreciate the uncertainties associated with any LCC
model and its application and note that these gaps can be addressed using sensitivity
and/or break-even analysis.

Having discussed the sensitive dependencies of the LCC study on timing and
economic uncertainties, it is also important to consider the financial benefits of LCC
in the long run. To illustrate this point, we consider a real-world scenario in which
vertical facade applications were considered for adoption based on their economic
viability. A representative example for such a study is the one conducted by SERIS on
the colored BIPV facades installed at the School of Design and Environment (SDE),
NUS campus, as a part of the first real-world test-bedding project in Singapore [11].

Based on empirical evidence as reported in [11], we note the following key
results that are representative of the general benefits regarding economic viability
and longterm financial performance, an LCC study can provide for an energy project.

1. Even though the initial investment for a BIPV facade is higher than the conven-
tional options such as cladding, the market value of the energy generated offsets
the difference in the initial investment over 7 years. On the contrary, the expen-
diture for the maintenance of conventional facades as compared with those for
the BIPV systems keeps accumulating, as a result of which conventional facades
become an expensive investment.

2. The implementation of BIPV systems (colored type) over the long-term, say
30 years, works out to be more economical compared to the conventional cladding
facades. Over this period, the LCC value of the BIPV facade can eventually drop
to almost half of the LCC value of the conventional facade which would have
increased significantly over time due to maintenance costs.

3. If the benefits of carbon emissions savings are considered, say in the case of
Singapore, the LCC value for BIPV systems can further decrease significantly.
3 Concluding Opinion

With rising consciousness about resource depletion and sustainable energy, innovative energy systems are required to capture and use incident solar energy on buildings. This transition to new technologies such as the BIPV discussed in this chapter should be preceded by a thorough understanding of the costs involved and the feasibility factors that determine the effectiveness of integrating these systems with the existing buildings in the long run. For example, measuring the impact of transitions to BIPV systems, involves parameters such as energy savings, reducing carbon emission, and breaking even financially. LCC provides an evaluatory model to largely understand and assist these transitions by critically examining the economic benefits and challenges of incorporating new technologies or methodologies into existing systems.

The LCC application illustrated in this chapter is relevant to tropical ecosystems wherein renewable energy sources such as solar energy is abundantly available. From a user perspective, this analysis is most suitable for architects, real estate developers, and property owners as they can tailor the integration depending on the cost-effectiveness of the BIPV system for various placement orientations and installation areas. LCC, in this case, provides a detailed breakdown of initial investments and recurring costs with the total amount of electricity generated over the life cycle of the system installed. It is also helpful in estimating carbon emissions avoidance and energy savings (due to its cooling effect) in the long run which signifies how greener BIPV systems are in comparison with the conventional energy sources.

In the context of CE, adopting innovative renewable energy sources such as the BIPV systems into urban ecosystems becomes important. It reduces the burden on traditional power grids that are mainly dependent on fossil fuels and consequently lowers the environmental impact of energy production and consumption.

Questions

1. Explain conceptually how the transition towards a circular economy in the energy sector can be realised.
2. Define LCC and LCOE.
3. Explain the need for solar energy systems such as BIPV modules in resource-stressed countries such as Singapore.
4. Consider a building that uses BIPV systems on its east and west exterior walls. The modules are spread over 250 m\(^2\) area on the upper half of each of the sides to capture the solar energy during the day. Using the online LCC tool posted by SERIS on the National Solar Repository (NSR) website (link below), estimate the LCC for such an implementation. Also, highlight with reason, any differences in LCC between this implementation and the case in which the BIPV module is installed on only one side of the building (area: 500 m\(^2\)), say east as illustrated in the chapter. The NSR tool can be accessed at https://www.solar-repository.sg/lcc-calculator.
Suggested Reading

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