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Multitasking Façade: How to Combine BIPV with Passive Solar Mitigation Strategies in a High-Rise Curtain Wall System

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Abstract

This paper outlines the processes and strategies studied and selected by the team during the design stages of the project for the incorporation of BIPV into the tower's façade. The goal was to create a system that helps reduce internal heating and cooling loads while collecting energy through photovoltaic panels located throughout the building.
The process used to develop this façade system can be broken down into three stages.
1. Concept: BIPV as design catalyst for a high-rise building.
2. Optimization: Balancing BIPV and Human comfort.
3. Integration: Incorporating BIPV into a custom curtain wall design.
The FKI Project clearly illustrates the evolution building enclosures from simple wall systems to high performance integrated architectural and engineering design solutions. This design process and execution of this project represent the design philosophy of our firm.

Keywords: BIPV- building integrated photovoltaic, Optimization, Integration, High-performance façades, Energy generation

0. Main Text

Completed in December 2013, the new head office building for the Federation of Korean Industries (FKI) is a major new addition to the skyline of Seoul, Korea. FKI represents major Korean companies such as Samsung, LG and Hyundai Motors. The new headquarters is located on Yeoi-Dae-Roh, the main thorough road in Seoul and is now a prominent fixture among the wall of marquee buildings. Directly across the street from Yeoido Park, the tower's position guarantees spectacular views on all sides, adding to the world-class setting similar to New York's Central Park or Chicago's Magnificent Mile.

The project is composed of two structures. The first is a 50-story, 245-meter tall office tower. The second is a 3 story conference centre that is attached to the main tower. The tower's interior includes several indoor garden and atrium spaces that enhance the workplace environment with natural elements of wood, bamboo and other native plants. The interior takes advantage of the floor-to-ceiling windows of the exterior wall, offering an abundance of natural light to office spaces and corridors, as well as extensive views of neighbouring Yeoido Park, the Han River and the surrounding city.

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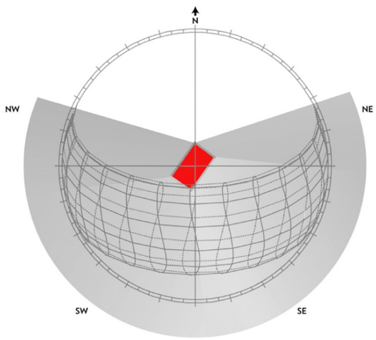
1. Concept: BIPV as Design Catalyst for a High-Rise Building

The concept for the FKI Tower was developed by combining the client's request for a highly efficient and rational building with the city's requirement that all new large-scale commercial buildings generate a minimum of 5% of their energy onsite. A strategy was developed that would meet both requirements, as well as reduce the amount of energy that the building used for its heating and cooling loads. The use of building integrated photovoltaic panels (BIPV) was seen as an architecturally appealing way to meet the strict zoning requirement, while the optimization of the panels became a driving factor in developing the architectural expression.

Geothermal, Solar, Wind, Fuel-cell, Hydro Power were the options allowed as part of the requirement stipulated by the city. The systems needed to be certified as New/Renewable Energy by National accreditation organizations, and also be the most practical and realistic for the building in terms of cost, constructability, and maintenance.

These requirements were seen as a great design opportunity and a number of ideas were investigated and measured. Solar power and geothermal were the two systems identified as both realistic and cost efficient methods of satisfying the city's requirements.

As the team began to explore the integration of photo-



[hide][hide]Climate data for Seoul (1981–2010)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high °C (°F)	1.5 (34.7)	4.7 (40.5)	10.4 (50.7)	17.8 (64.0)	23.0 (73.4)	27.1 (80.8)	28.6 (83.5)	29.6 (85.3)	25.8 (78.4)	19.8 (67.6)	11.6 (52.9)	4.3 (39.7)	17.0
Daily mean °C (°F)	−2.4 (27.7)	0.4 (32.7)	5.7 (42.3)	12.5 (54.5)	17.8 (64.0)	22.2 (72.0)	24.9 (76.8)	25.7 (78.3)	21.2 (70.2)	14.8 (58.6)	7.2 (45.0)	0.4 (32.7)	12.5
Average low °C (°F)	−5.9 (21.4)	−3.4 (25.9)	1.6 (34.9)	7.8 (46.0)	13.2 (55.8)	18.2 (64.8)	21.9 (71.4)	22.4 (72.3)	17.2 (63.0)	10.3 (50.5)	3.2 (37.8)	−3.2 (26.2)	8.6
Precipitation mm (inches)	20.8 (0.819)	25.0 (0.984)	47.2 (1.858)	64.5 (2.539)	105.9 (4.169)	133.2 (5.244)	394.7 (15.539)	364.2 (14.339)	169.3 (6.665)	51.8 (2.039)	52.5 (2.067)	21.5 (0.846)	1,450.5 (57.106)
% humidity	59.8	57.9	57.8	56.2	62.7	68.1	78.3	75.6	69.2	64.0	62.0	60.6	64.4
Avg. precipitation days (≥ 0.1 mm)	6.5	5.8	7.4	7.8	9.0	9.9	16.3	14.6	9.1	6.3	8.7	7.4	108.8
Sunshine hours	160.3	163.3	189.0	205.0	213.0	182.0	120.0	152.5	176.2	198.8	153.2	152.6	2,066.0

Source: Korea Meteorological Administration [20]

voltaic panels into the façade of the tower, two major constrains were uncovered regarding how the zoning and architectural expression impacted the optimization of the system.

The first was the zoning requirement that the buildings primary orientation be aligned with the street grid of the Yeoido district. It also required that the tower be located on the property line facing the large public park adjacent to our site.

This urbanistic requirement was stipulated in order to maintain the street wall created by all of the other towers that face directly the park. It placed the building in what can be called an environmental disadvantage. As part of the original site and environmental analyses, it was understood that in order to maximize the building's potential for energy generation, a way to expose as much of the building's facade to the direct radiation of the sun had to be established.

This would be much easier to achieve if the tower could be rotated off the city's grid so that its broad side faced directly south and moved the tower back from the property line. This change would allow for the tower to not be in the shadows of the adjacent buildings. In its final orientation, the tower is at 45 degrees from true north.

The second constraint was both driven by the planning guidelines and reinforced by the client. The architectural expression and form of the building needed to have a contextual relationship to the predominantly orthogonal architecture of the Yeoido district. The building's shape needed to be rectangular box and work aesthetically with its neighbours. This meant that we were not able to shape the tower in ways that would help maximize its exposure to the sun. The Tower needed to be a traditional rectilinear office building that is functional and efficient.

After the Towers form and location on the site were finalized, two areas of façade were identified for the integration of photovoltaic cells. The first was the spandrel zones on each floor, which equal 16,377 SM of surface area and could accommodate 240,156 5"x5" Monocrystalline silicon. The second was the roof of the tower that has a surface area of 2,353 SM with 46,145 5"x5" Monocrystalline silicon. The first analysis estimated that the two surfaces combined could have a daily power output of 2,110 KW and an annual output of 780 MW. These numbers would be further verified as the design was tuned in later stages.

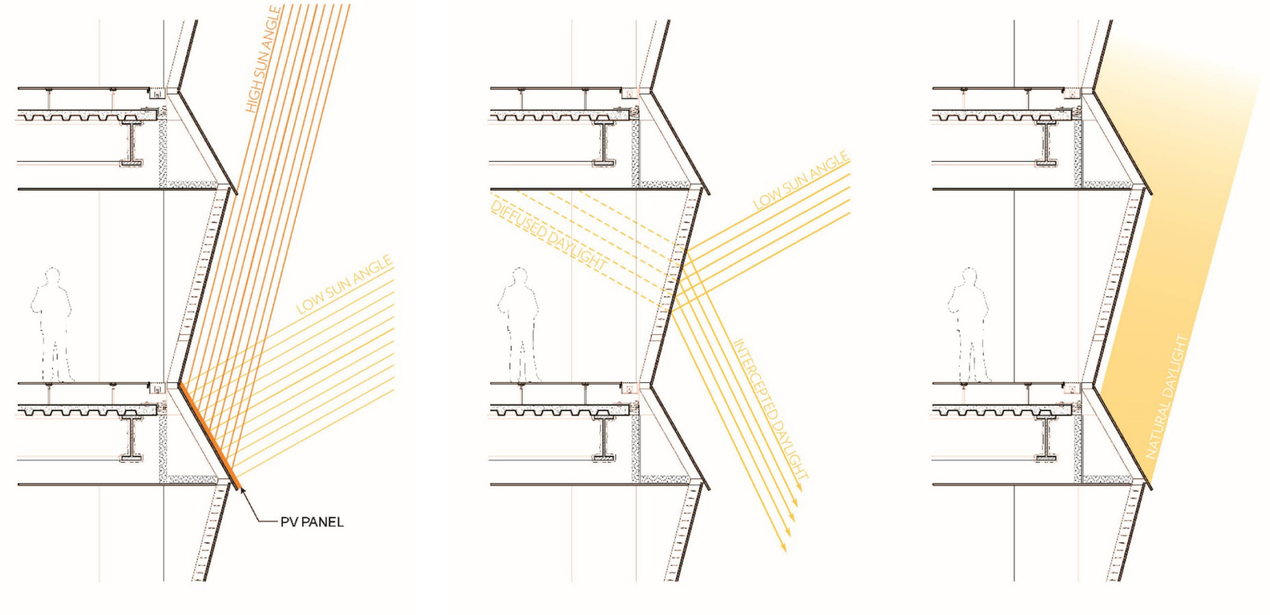
While the city of Soul set the rules for power generation, it also created an incentive program where buildings can take advantage of the local Renewable portfolio Standard (RPS), which allows FKI to sell Renewable Energy Certificates on the local market. At past historical market rates, the FKI building was eligible for up to ₩180,060,000/yr. in value from REC's sold on the market. This additional financial benefit would result in a net energy cost reduction of 36.6% from the baseline building.

This incentive allowed the payback for the BIPV panels, which would have typically been 30~35 years to be reduced to about 7 years due to these incentives.

Table 1. Calculation of payback using KEPCO incentives

Location	Cost of PV Spandrel Panel per sm [krw]*	Cost of Non-PV Panel per sm [krw]*	Incremental difference [krw]	Efficiency of panel due to solar orientation*	annual output in kwh	Payback per sm [krw]**	Payback period in years
Southeast Façade	₩738,000	₩500,000	₩238,000	79%	367,646	₩35,686	5.57
Southwest Façade	₩738,000	₩500,000	₩238,000	77%	210,788	₩34,742	6.85
Roof	₩1,048,000	₩750,000	₩298,000	95%	146,675	₩42,937	6.94
Average							6.82

*based on mfg. estimate **assuming buyback rate of ₩536 krw / kwh



PV POWER GENERATION
The specific angle of the PV panel maximizes the power output potential of the tower.

GLARE MITIGATION
The positve tilt of the vision glass panel allows for the deflection of low sun angle glare.

SOLAR REDUCTION
The shingle wall provides self-shading that reduces high sun angle direct solar radiation.

2. Optimization: Balancing BIPV and Human Comfort

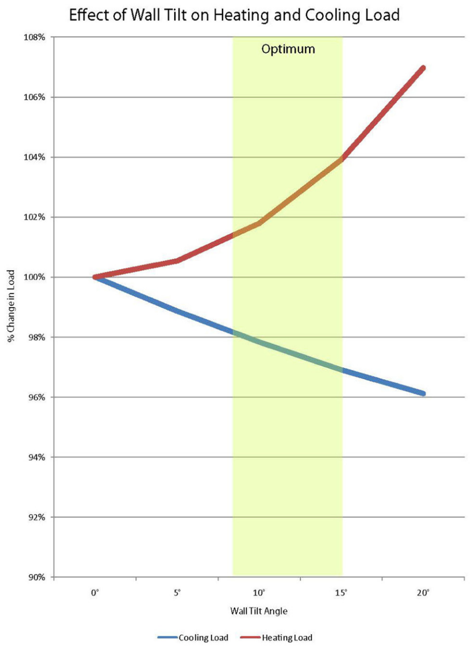
The second step in the design process was the integration of BIPV into the building's façade. The goal was to optimize a balance between the performance of the BIPV and Human comfort. This goal was achieved by developing the form in a way that increased power generation, improved glare mitigation and reduced the amount of direct solar radiation that enters the building through the glass.

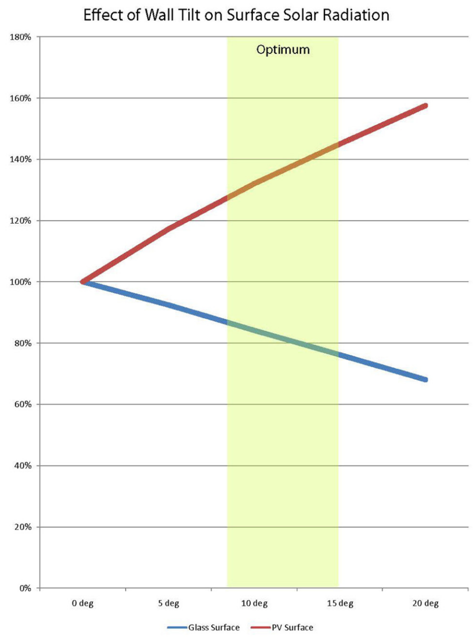
The search for balance between the performance of the BIPV and Human comfort became a function of the relationship between the angle of the vision glass and the spandrel panel. The project engineer's research determined that the system would function best with an angle between 10~15 degrees. The best performance was at the 15 degree slope. As expected the performance of the PV panels continue to improve as the angle of the spandrel panel increased. Even in temperate climates, summer cooling loads are greater than winter heating loads in large office buildings, so designing for shading is critical. However, tilting the façade beyond 15 degrees causes the heating loads to increase at an accelerated rate due to increased surface area. Therefore the 15 degree slope, where the heating penalty and cooling gain were approximately even, was determined to be the optimal solution. An economic advantage to maintaining the glass slope to 15 degrees or less from vertical is still defined as "vertical glass" as per the International building Code (IBC) as opposed to "sloped glass" that would have imposed more stringent design criteria.

The result is a reduction in the cooling energy by 5% (13.1 kWh/m² to 12.5 kWh/m²) and an increase in heating energy by 3% (53.8 kWh/m² to 55.3 kWh/m²). There is energy savings in cooling, fans, pumps, and heat rejection of a total of 1.5 kWh/m²/yr. but it is offset by the increase in heating energy of 1.5 kWh/m²/yr. caused by the reduction in solar heat gain during the winter in a heating dominated climate. However, since the electrical cost of cooling is more expensive than the natural gas cost of heating, there is a net energy cost reduction of 1.0%.

Another benefit of turning the spandrel panel toward the sky is the reduction of glare and the heat gains from direct sunlight. With the exception of the early morning and the late afternoon periods, the building will be able to use the geometry of the exterior wall to self-shade the perimeter spaces that would normally be inundated with direct sunlight. This gives the building occupants the flexibility to open the shades and allow indirect natural light to illuminate these spaces. With a maximum lease span of 12meters; the majority of the building occupants would benefit from the increase natural illumination. This will also reduce the building's dependency on artificial light; substantial reducing the energy consumption of the tower.

To help mitigate the direct radiation issues automated blinds were incorporated. The blinds work to minimize summer solar heat gain while also minimizing glare. The 40% transparent automated blinds lower when incident solar radiation on the building facades exceed 200 W/m^2. Although daylight is desired in the winter to help reduce the heating load, if the incident solar radiation exceeds 600 W/m^2 or the illumination exceeds 1000 lux then the blinds are automatically lowered to reduce glare on the



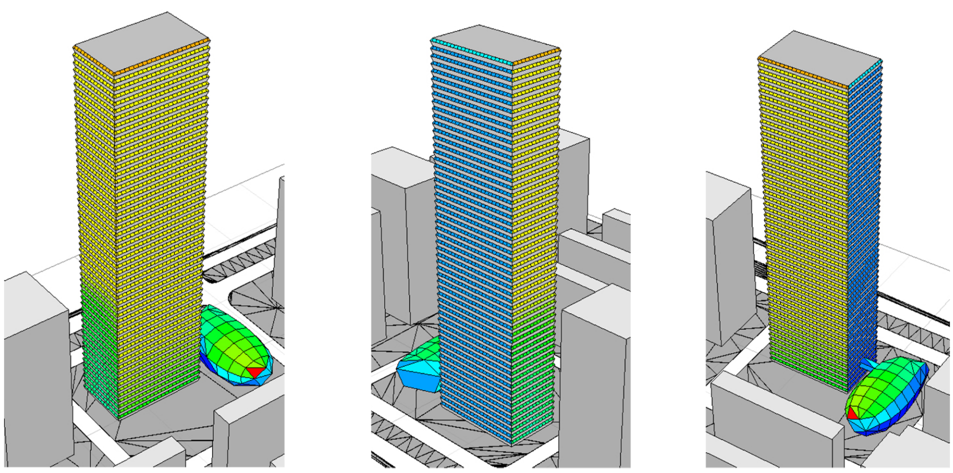


working plane. The use of automated blinds reduces the cooling load by 9% (11.8 kWh/m^2 to 10.7 kWh/m^2) and the energy of the fans, pumps, and heat rejection by 5% (26.5 kWh/m^2 to 25.1 kWh/m^2). Using the automated blinds to reduce the effects of glare on the work surface increases the heating energy by 3% (37.9 kWh/m^2 to 38.9 kWh/m^2).

Another factor that played a role in the selection of the angle of the wall was the physical comfort of the inhabitants standing against a glass wall that is tilting out towards the ground. The client's team was concern for the safety of the office workers and how they would feel standing against a wall that was leaning. None of them had ever seen a building where the façade tilted away from the space and down towards the street. To try and alleviate this concern, a full scale mock-up of a 3 m wide full floor panel that could be adjusted to multiple angles were constructed by the façade contractor. This study help convince the client that safety was not an issue and also help them feel at ease with the relationship people were going to have with the building's exterior wall.

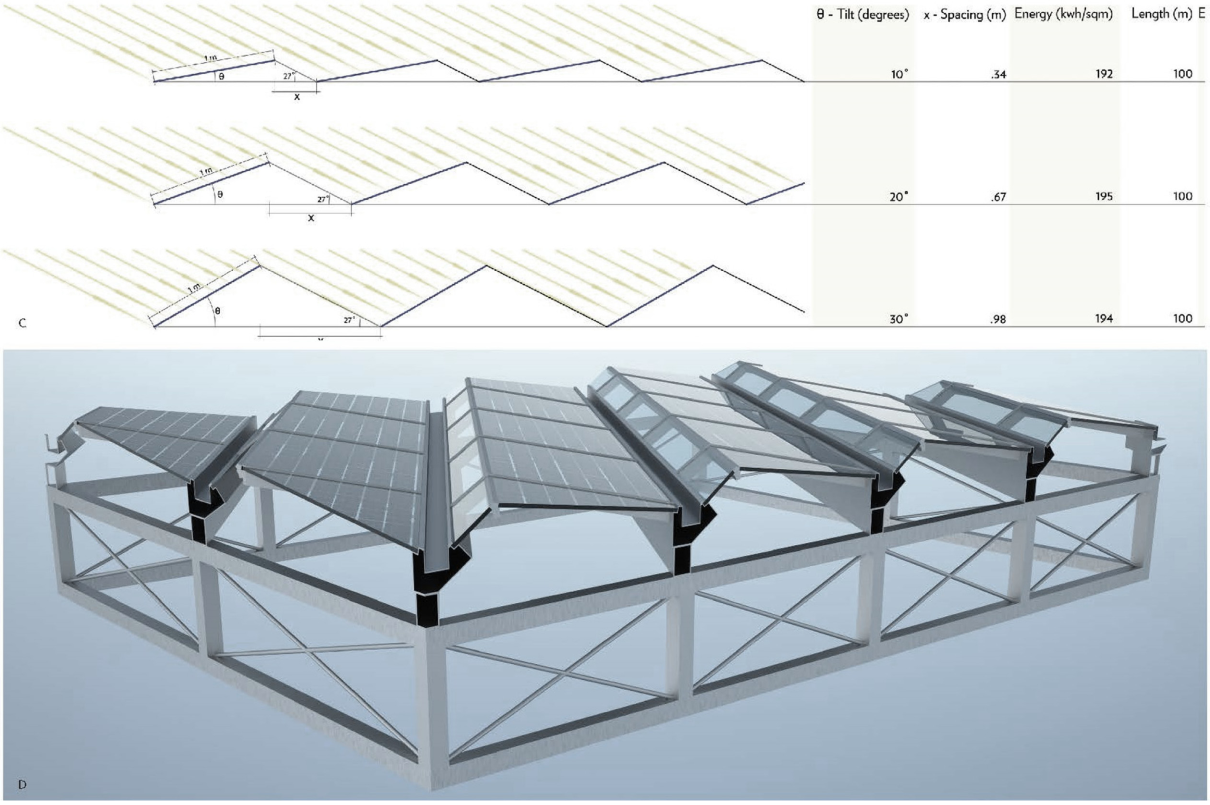
3. Integration: Incorporating BIPV into a Custom Curtain Wall Design

Once the principle for the overall design concept and the faced system were set, an Ecotech® model was used to determine the optimal areas for incorporating the BIPV.



South West East

Solar Analysis: Direct Radiation



The client made a financial decision to use photovoltaic technology that only was able to generate electricity from direct radiation. Due to the building's orientation it was understood that not all four faces of the tower would be able to generate enough electricity to justify the expenditure of the BIPV panels. Both the amount of direct radiation and total radiation were analysed and it was determined that BIPV would be best used on the southeast and southwest faces. The analyses also showed two other areas were the BIPV should not be used. These areas included the three lowest levels of both sides due potential interference from tress and other ground based obstructions and on the southwest façade below the 14th floor due to the proximity of the surrounding buildings.

Since not all faces of the building were currently suitable for the selected BIPV technology. It was important to propose a design that allows for the BIPV panels to be added in the future as new technology became available that can take advantage of indirect radiation. For this reason, the spandrel panels were design as shadow boxes in which the BIPV panels were floated above an insulated spandrel panel. This design feature allowed for maximum flexibility in the use of BIPV. Where it was determine that power generating units were not suited, a glass panel with a frit pattern similar to the BIPV was used so there wouldn't be a significant change in the buildings expression.

Another area that was particular important in the integration of the concept was the layout and size of the BIPV panels. The final size of the spandrel panels was based on the layout that would maximize the number of 5x5 Monocrystalline silicon cells. The façade was designed as a unitized curtain wall system and because the tower is intended to be used as an office building, a 1.5 m module of was selected. Multiple options were studied and it was determined that three BIPV panels in a 3 m curtain wall module generated the most efficient layout. A total of 1,130 BIPV panels with 211,883 5x5 Monocrystalline silicon cells were used. As with any shadow box design, heat mitigation would be an issue that needed to be addressed. The BIPV system generates a significant amount of heat of the back of the cells. Instead of allowing the heat to enter the building and be mechanically removed, it was decided that a 25 mm gap would be placed between the three BIPV panels on each wall module, allowing for the heat to naturally dissipate into the air.

The 3 m wide by 4.5 m tall curtain wall panel also created complications in its transportation from the factory to the site. Several options for separating the panels into multiple segments were studied. The most logical idea was to create two smaller panels, one for the vision area and a separate panel for the spandrel (BIPV) segment. At the end, it was decided that trying to install and create a rigid connection between to separate panels that tilt in different directions would become a bigger change. Another complication with the curtain wall panels was the weight of large glass panes. By tilting the vision glass down towards

the ground, we had inadvertently increased its natural deflection. In order to maintain the required glass flattens, a much ticker and costly glass assembly would be needed. In order to avoid this increase in cost and complexity it was decided that the size of the glass would need to be reduced from its original 3 m × 3 m. We used this requirement as an opportunity to deal with two design issue that had not been resolved. The first one was the need for a guardrail that would typically be required @ 900 mm above the finish floor in buildings with all glass façades. Instead of adding the commonly used tubular rail, the original glass panel was broken at this location with a horizontal mullion. This alleviated the need for the guardrail and generated two smaller glass panels that were needed in order to reduce the weight of original glass. The upper "vision" panel became 2.1 m tall by 3 m wide; maintain the original intent for a large vison panel. The lower panel was broken further separated into two smaller panes of 900 mm tall by 1.5 m wide. This was done so that we could satisfy the client's requirement that the design include operable windows. Each curtain wall panel would now have one mechanically operable window.

The other area of the project that included BIPV was the roof of the tower. With a surface area of 2,353 sm and at 245 m above grade, the roof of the tower would have unobstructed exposure to the suns direct radiation. The other advantage that the roof had over the spandrel areas is that the PV panels on the roof could be rotated to face directly south. The design didn't need to adhere to the grid of the city or the orientation of the tower. The only constraint was the size of the roof.

The first step in the design was to understand the relationship between the angle and the spacing of the panels in order to maximizing power generation. One row of panels should not shade the row located right behind it, as this would create significant reduction in their power output. To arrive at the right balance, a set of spacing to angle relationship analyses were conducted using both direct and total radiation. While power output per square meter of PV was very similar for all angles, it was found that a 10 degree tilt could allow more panels in a smaller area with minimum self-shading, thus creating a larger overall output.

One of the unique aspects about the roof is that directly below are two publically inhabited spaces. Two thirds of the space is occupied by a roof garden that is designed as a public space for the building's tenants. The other third is allocated for a destination restaurant that would have views to the entire city. The goal was to develop the roof as a skylight system that allowed for the occupants to see out to the sky while using the PV panels as frit pattern to help reduce heat gain in the space. From the inside, the roof would appear as a glass shingle skylight with PV panels providing shade. One of the unexpected surprises is the patterns created by the PV cells that can be seen in the under structure and core walls around the garden.

One important difference between the two spaces is that the garden needed to be an outdoor space with natural ventilation, while the restaurant space would be a fully enclosed room. The goal was to create a skylight system that could be simply modified to serve both enclosure requirements. The system that was developed is composed of three primary components. The first is the BIPV panels that face directly south and are angled 10 degrees to face the sun. The second is a clear glass panel that faces north and allows for indirect light to enter the spaces below. In the roof garden this panel is removed to achieve naturally ventilated requirements. The third component is gutter that lies between the two angles panels and collects rain water that can be used for irrigation of the gardens.

In conclusion it's important to point out that he FKI Project clearly illustrates the evolution building enclosures from simple wall systems to high performance integrated architectural and engineering design solutions. The tower has been certified Superior Grade, which is the equivalent to LEED-Gold in Korea.

Some of the most notable metrics achieved by the project are:

- The building integrated photovoltaics (BIPV) on the facades and the roof annually convert a total of 844,028 kWh of energy from sunlight to electricity. The 844,028 kWh account for a total savings of 3% (5.3 kWh/m^2 out of 177.7 kWh/m^2) of the building energy use intensity and a cost savings of 3.4%, ₩76,715,908.
- The tower can generate enough energy to power 274 households for an entire year and will reduce carbon dioxide emissions by 394 tons per year.
- The average energy generation per day is 2,110 KW and 780 MW a year. The regional energy reduction per Energy Star Target Finder predicts a 25.3% energy-use reduction and a 31.3% overall energy-cost reduction when compared to similar projects.
- FKI Tower's BIPV system currently runs about 20% of the tower's overall lighting and around 7.2% of the tower's overall electric use.
- The tower has 632 parking spaces, 32 of which have electric car charging stations - the building has nearly 9% of all electric-charging stations in Seoul.
- 10% of the energy savings in FKI Tower come from the advanced geothermal system.

We strive to create intelligent, high-performance, forward-looking designs that exhibit timeless and enduring qualities. We believe that the future of architecture relies not on a changing aesthetic but on the implementation of integrated processes, predicated on an equal understanding and consideration of each project discipline.