Proposed Model for Constructional Design of Photovoltaic Integrated Steep Roof Systems and Case Study: Istanbul, Turkey

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Abstract

Energy consumption in buildings constitutes a considerable part of the total energy consumption in Turkey and electricity constitutes 25% of the energy consumption in buildings. Moreover electricity is the most responsible energy sector for green house gas emissions in Turkey. Energy production by renewable energy sources in buildings was recently referred in energy efficiency policies in Turkey. As a renewable energy technology, photovoltaic (PV) can be replaced with conventional construction materials and this sustainable technology is called Building integrated photovoltaic (BIPV). Roofs are frequently the most attractive opportunity for BIPV installations because of their substantial solar access. Even though there are many constructed BIPV roof systems worldwide; there is only one example in Turkey. This indicates that BIPV is not a common application in Turkey. However, there are some examples of PV applications, in which PV modules are not integrated in the projects during the design process, but they are added during the use of the buildings for retrofit applications. Thus these examples include standoff PV modules attached on roof systems. This design decision results in loss of opportunity of replacing standard construction roofing material with the BIPV system. There are financial barriers on BIPV installations in Turkey. However recent improvements regarding the support of renewable energy source indicate that BIPV applications will be more affordable in future. In this case, lack of experience on the constructional design of BIPV applications may result in improper designs and incorrect detailing of PV roof systems. In addition there is not a guide, regulation or standard regarding the construction of PV systems used in buildings in Turkey. In order to overcome this issue, a model has been developed for the constructional design of PV roof systems, which assists architects, constructers and roof covering material producers to develop correct design alternatives for PV integrated steep roof systems and based on the model, a case study in which PV integrated steep roof system alternatives are designed for Istanbul, Turkey. 5 alternative roof systems were designed with standard PV modules partially integrated in a steep roof system, and their visual impacts, ventilation rates, material consumption rates, self cleaning rates and ease of disassembly are also discussed.

Keywords: photovoltaic, building integrated photovoltaic, renewable energy, roof systems

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1.1 Introduction

In Turkey, 70% of electricity production is supplied by thermal energy and 85% of the thermal energy is being produced from fossil fuels, (Ogulata, 2002). According to 2005-2006 Turkey Energy Report, which was published by World Energy Council Turkish National Committee at 2007, electricity is the most responsible energy sector from green house gas emissions in Turkey. Energy consumption in buildings constitutes almost 30% of the total primary energy requirements and electricity constitutes 25% of energy consumption in buildings, it is the second energy source followed by the natural gas with 29%, (UCTEA, 2008). United Nations Framework Conventions on Climate Change (UNFCCC) was signed by Turkey at 2003 and Turkey signed Kyoto Protocol recently at 2009. This protocol restricts Turkey to decrease green house gas emissions. As well, Turkey has to import nearly more than half of the energy requirement from abroad to meet her needs. In addition, the growth of Turkey's industry is giving rise to a substantial increase in energy demand, (Ogulata, 2002). As a result, renewable energy sources and energy efficiency gained importance in Turkey due to increasing energy demand and environmental concerns.

It was in the year of 1970 when "TS 825 - Conservation Rules of Heat Effects for Buildings" standard regarding thermal insulation of buildings had been activated. In the following years this standard has been revised to increase the U values of the building envelope. Regulation titled "Thermal Insulation in Buildings" has been activated in 2000. The law regarding "Using Renewable Energy Sources for Electricity Generation" has been activated at 2005. A feed in-tariff to renewable energy production which is 5,5 euro cents/kWh for 10 years has been imposed by this law. At 2007, "Energy Efficiency Law" was published and in this law, producing energy by renewable sources is mentioned as an energy efficiency topic. Energy production by renewable energy sources in buildings was first referred in "Energy Performance Regulation for Buildings" regulation at 2008.

As a renewable energy source, photovoltaic (PV) can supply all or a significant part of the electricity consumption of a corresponding building without depletion of finite fossil fuel resources. Hence, they emit no pollution and no greenhouse gases. In order to save on building materials and reduce ecological footprint of buildings, PV can be used instead of conventional roof coverings. This combination of technology and architecture is called Building Integrated Photovoltaic (BIPV). Roofs are frequently the most attractive opportunity for BIPV installations because of their substantial solar access. The benefits of BIPV roof systems are not only functioning as building envelope and generating electricity, but also they do not require any extra land area and infrastructure installations for electric generation. Additionally, losses of electricity during the transmission and distribution are reduced due to short distance between generator and electricity consumer. The first installation of BIPV was carried out in 1991 in Aachen, Germany. The PV elements were integrated into a curtain wall facade with isolating glass, (Benemann, et al., 2001). Following the initial steps in Germany, many BIPV projects were carried on especially in Europe, Japan and USA by support funds of governments and various communities. In 1996, six PV integrated roofs were constructed in Nieuw Sloten, Netherlands, Figure 1a. This was the first city district in the world, where BIPV was demonstrated on such a large scale (Schoen, 2001). In 1999, the worlds' largest urban PV project, Nieuwland was designed and constructed again in Netherlands, Figure 1b. The project consists of over 500 houses and several other buildings with PV modules integrated in their roofs (Pvdatabase, n.d.).

(a) (b) (c)

Figure 1: PV integrated roof system examples.

Although Turkey is one of the regions, which has the most solar electricity generation potential in the Europe (above 1200 kWh/kW per year), (Šúri et al., 2007), and that the benefits of PV integrated roof systems are very well known, there is only one example of PV integrated roof system in Turkey. This PV integrated roof application was constructed on the south faced part of the Mugla University cafeteria building's roof in 2003, Figure 1c. The area of PV covered roof surface is 215 m2. Remaining examples of PV roof systems include systems in which PV had not been integrated to the roof system as a building material but had been attached on the roof coverings of low-slope roofs. Additionally, they had been added during the use of the buildings. This design decision had resulted in loss of opportunity in replacing standard construction material with the BIPV system. The main reason why PV integrated roof systems is not a common application in Turkey is due to financial issues; i.e. initial investment cost is high and payback period of the initial investment cost is too long. Unfortunately financial supports at the governmental or municipality level are not sufficient for the installations of PV roof systems in Turkey. The feed in-tariff to renewable energy production which is insufficient (5,5 euro cents per kWh for 10 years) was implemented recently in 2005. Law proposals regarding the increase of the feed in-tariff are being discussed nowadays by Turkish Ministry of Energy and Natural Resources. Finally, Turkey signed Kyoto Protocol in 2009, which restricts her to decrease green house gas emissions. The aim of this development is to make PV applications more affordable and hence more common. However, when affordable, it will be a challenge for Turkish architects, who are only familiar with the design of PV attached onto the roof coverings of only low-slope roof systems, to design a PV integrated roof system, particularly detailing of the PV modules with the remaining roof components.

Although there are standards regarding the use of solar energy for heating (TS EN 12975 Thermal solar systems and components - Solar collectors, TS 3817 General Requirements for Solar Water Heaters, TS ISO 9459 Solar heating-Domestic water heating systems), there are not any standards or regulations about generating electricity by solar power in buildings. “Energy Performance Regulation for Buildings” and in “Energy Efficiency Law” provide typical details for the design and construction of thermal insulation materials for buildings; and, unfortunately there is no such a guide for the construction of solar power systems for buildings in Turkey.

In order to overcome the above given issues, a model has been developed for the constructional design of PV roof systems, which enables architects to develop correct design alternatives for PV integrated low-slope systems, PV attached on steep roof systems and PV integrated steep roof systems in addition to already known PV attached on low-slope roof systems. The model comprises design processes and inputs for each design process for the architect for the selection of an appropriate type of PV roof system for the building. This paper presents only the sub model proposed for the constructional design of PV integrated steep roof systems and based on the model, a case study in which PV integrated steep roof system alternatives are designed for Istanbul, Turkey.

1.2 Proposed model

Figure 2 illustrates the flowchart of the proposed model developed for the design of PV integrated steep roof systems. Initially, PV module type and PV array size are determined. Module type can be selected according to power output, cell type, number of cells per module, visual impact, module size and module substrate materials. Power output is determined by cell type and also by the module size. Each cell type has different efficiency rate. There are monocrystalline (%14-17 efficiency), polycrystalline (%13-15) and amorphous silicon (%5-10) cells used in PV modules. PV array size is determined according to total energy demand and budget.

Subsequently, PV array orientation and slope, which affect the energy efficiency performance of the PV system, are chosen. Typically, the most favourable orientation is south in the northern hemisphere and north in the southern hemisphere. When the PV surface is perpendicular to sun’s rays, they receive the maximum solar radiation. Based on this knowledge, an optimum tilt angle (slope of the PV system) is defined to generate maximum electricity for whole year or for a specific period of the year (e.g. summer). This decision is dependent on the use period of the building. Additionally, PV modules can be mounted on a movable or sun tracking systems in order to gain a higher yield. Tracking systems are generally used in sun shading systems and systems attached on low-slope roofs. PV simulation programs, which utilize meteorological data based on monthly or hourly measured irradiance, can be used for the calculation of the optimum tilt angle. Some of the commonly used PV simulation

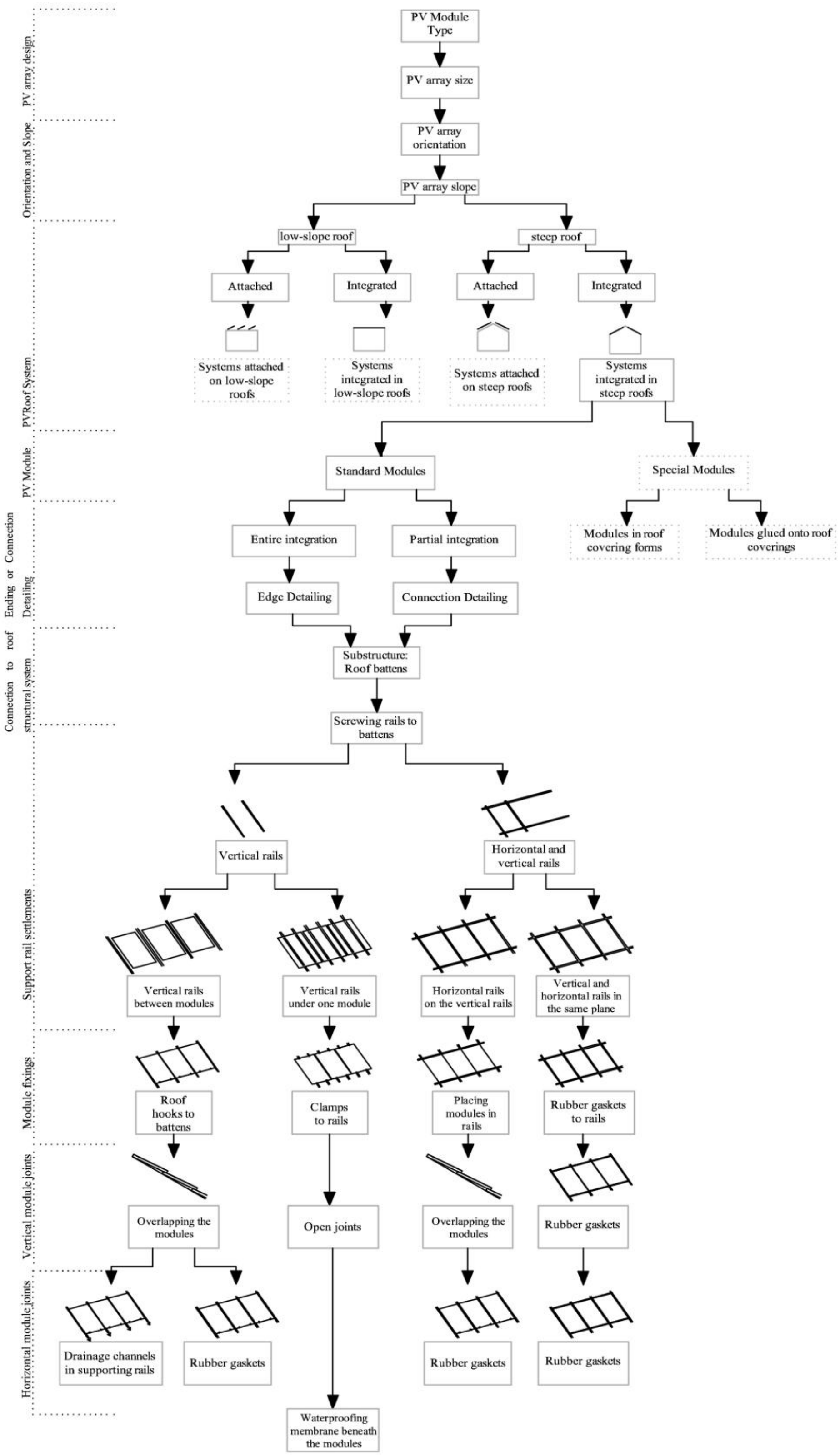

Figure 2: Proposed model for the constructional design of PV integrated steep roof systems

programmes are PV-DesignPro (Mauisolar Software), PV SOL (Valentin EnergieSoftware), PV F-chart (F-Chart Software) and PVSYST software for photovoltaic systems (University of Geneva).

Following, the slope of the roof system is determined based on the criteria, which are climatic conditions, surrounding buildings' roof slopes, roof coverings, local construction methods, regulations and particularly PV array slope. The roof system may be determined as a low-slope or a steep roof system. For example, if the decision making process results in a low-slope roof; i.e. the roof system would be built at a location where the rain intensity indicates dry conditions, and the defined PV array slope remains higher than the defined slope of the roof; then the PV array can be attached at the determined slope separately on top of roof covering of the low-slope roof. On the other hand, if the decision making process results in a steep roof system, the slope can be arranged at the same slope of the PV array and then, the PV array can be attached separately on top of pre-constructed roof covering or be integrated in the roof system as a roof covering, Figure 2. Whether the PV array will be attached or integrated in the roof system are determined according to energy generation efficiency, visual impact, less material consumption, ease of transport, ease of mounting, speed of installation, less tool usage, less labour need, safety during installation, self cleaning, ease of module disassembly in the case of maintenance, etc.

When integration of PV arrays in the roof system as a roof covering is considered, two types of PV modules can be used as a roof covering. These are standard modules and special modules. Special modules are formed like a roof covering or they are glued onto the roof coverings. Special modules are smaller than standard modules. Although the cable consumption increases by the use of these small modules due to cabling per module, they are preferred due to their visual effect. In addition, they are light and their transportation is easier than standard modules. Since standard PV modules are the most commonly produced and used ones in Turkey, the progress of the proposed model will proceed with this type of module in this paper. Standard modules can either be entirely or partially integrated to the roof system, example details are provided in Figure 3. This decision is based on the intended PV array size and roof area. If the roof area is larger than the PV array area, then a partial PV array integration must be considered.

Edge (ending) and connection details differ according to entire or partial PV array installation, as given in Figure 3. The borders and the seams between the last module and the roofing tiles must be ensured to be weatherproof. Weatherproof connections are achieved by metal (tin, zinc or lead) connection plates (flashings) and flexible flashing strips. Generally, connection plates should be specially produced to suit the project. Flexible flashing strips are made from Polyisobutylene (PIB - rubber) with an aluminium rib mesh insert and butyl adhesive strips along both edges.

Standard PV modules are connected to the steep roof structure with a substructure. This substructure enables mounting independently of the rafter spacing and also enables ventilation under the roof covering. An existing roof substructure with suitable spans can also be utilized for construction of the modules. Usually roof battens are used as a substructure. Moisture

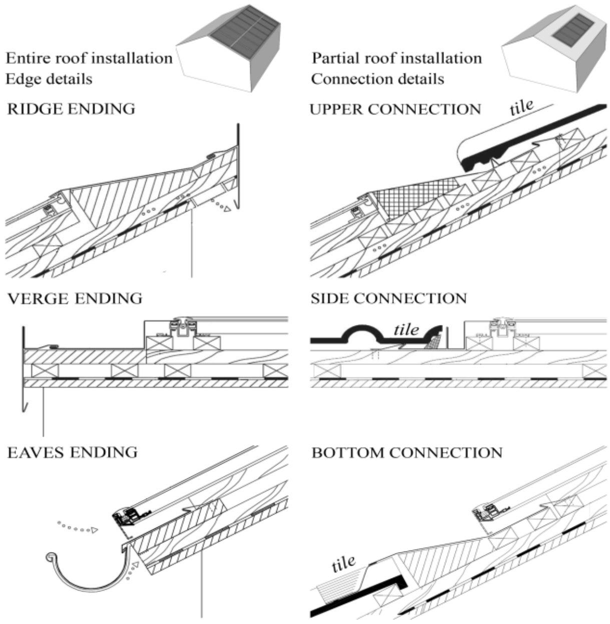

Figure 3: Details of entire and partial PV integrated roofs (Solar World AG, 2008***)***

damage of the components of the roof system due to the condensation occurring at the rear of the modules requires sufficient ventilation behind the modules. Cold roof system, which is usually designed in steep roofs, generally permits rear ventilation. However, the module efficiency decreases in high temperatures, thus the ventilation also affects the efficiency of the system. Ultimately, decision must be taken, whether the existing substructure is going to be used or a new substructure is going to be constructed according to spans and ventilation.

Support rails which are screwed to the roof substructure are used for module fixing. Modules can be placed in or attached on these rails. Supporting rails can be located in four different types. When only vertical rails are used, rails can be located between the modules or vertical rails can be located beneath the modules, Figure 2. In the third type of settlement, horizontal rails are used on the vertical rails. Otherwise, vertical and horizontal rails can be situated in the same plane; a plain roof surface is achieved with in this type of settlement. Settlements are formed due to the module dimensions (spans), impermeability in joints (drainage channels, rubber gaskets, overlapping fashion or open joints) and appearance of the roof surface (overlapping or plain fashion, open joints). In addition to the given factors, material consumption should be taken into account.

Vertical rails located between the modules can be used with module hooks to fix the modules. Module hooks are mounted on roof substructure and modules are fastened in these hooks. Modules overlap each other by these hooks, Figure 4a. In vertical module joints, water tightness is achieved by this clapboard fashion and with rubber seals between the modules. In horizontal module joints, impermeability is ensured by drainage channels on vertical rails or with rubber gaskets attached to vertical rails, Figure 2.

Another settlement type with vertical rails located beneath modules is used with clamps to fix the modules. Modules are clamped to rails in points, Figure 4b. These point fixing is used when module joints are preferred to be left open. In either case, a waterproofing membrane must be used under the rails. Ventilation underneath the modules can be achieved easily with these open module joints.

In the settlement that horizontal rails are placed on the vertical rails, modules are placed in these horizontal rails, Figure 4d. This type of settlement ensures overlapping the modules in the clapboard fashion. Thus vertical module joints' water tightness is achieved by this clapboard fashion and with rubber seals between the modules. In horizontal module joints, impermeability is ensured by rubber gaskets attached to vertical rails, Figure 2.

When vertical and horizontal rails are situated in the same plane, modules are fixed with rubber gaskets attached to the rails, Figure 4c. Vertical and horizontal module joints' water tightness is also achieved by this rubber seals between the modules. A plain roof surface is achieved with this type application.

Module joint alternatives (open joints, overlapping settlement and flat settlement with rubber gaskets) must be evaluated according to the properties such as visual effect, ventilation rate, ease of installation, speed of installation, labour need, self cleaning and ease of module disassembly.

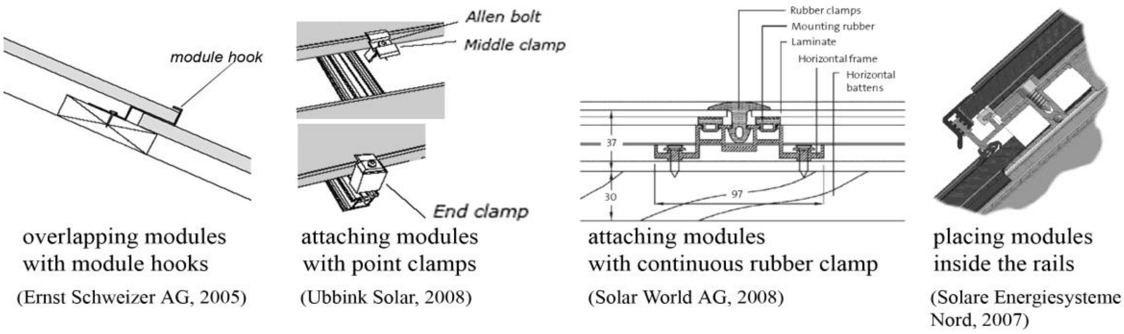

Figure 4: Module fixings

1.3 PV integrated steep roof system alternatives for Istanbul

A PV integrated roof system is designed for a new building in Istanbul, Turkey. The building is located in Kemerburgaz, which is a suburban area of Istanbul. The function of the building was determined as a residence. Initially, the roof was considered to be a steep roof due to building typology, snowy and rainy climatic conditions of the location and surrounding buildings' forms. Timber was selected as a local construction material. The roof structural system was considered as built-up timber roof. 5-cm thick expanded polystyrene thermal insulation material was designed between timber rafters to provide the required thermal resistance value of the roof system determined by Turkish Standards (TS 825- Thermal insulation requirements for buildings). An APP modified bituminous waterproofing membrane with a thickness of 4-mm was designed on the rigid thermal insulation material and rafters to prevent rainwater entry. Another APP modified bituminous waterproofing membrane with a thickness of 4-mm beneath the rafters was designed as vapour barrier to prevent the occurrence of condensation on the rear side of the waterproofing membrane.

Module type can be selected according to power output, cell type, number of cells per module, visual impact, module size and module substrate materials. PV array size is determined according to energy demand and budget.

PV modules' power outputs vary due to their dimensions, cell types and number of cells in a module. Thus a polycrystalline silicon glass-film framed PV module (80W etc.) was selected due to our total power demand and possible array area. Ease of procuring is also another factor affecting our selection. PV array size is determined based on financial limitations and energy demand. PV array orientation was determined as south to generate maximum energy. Optimum tilt angle in Istanbul for whole year was calculated by PVSYST simulation program. The simulation program specified PV array slope range as 26°-30°.

Building typology, snowy and rainy climatic conditions of the area and surroundings suggested the roof system form as steep roof. PV array was decided to be integrated in the roof system as roof covering due to less material consumption and integrated visual impact. Thus roof slope was arranged at the same slope of the PV array. However, Istanbul construction regulation (bylaws) states that the maximum roof slope can be up to %45 (24°). Therefore, the PV array and roof system slope was determined as 24° for maximum energy generation. As PV module type, standard PV module was selected due to ease of supply and less cable consumption according to its larger sizes than special PV modules. The array size was determined smaller than roof area. Therefore, a partial PV integration system was designed. Connection plates were specially designed to suit the tiles, which cover the rest of the roof. As a new construction, the substructure of the roof (roof battens) was designed according to module spans.

After the above given steps, the rail arrangements, module fixings and joints are studied with possible alternatives. The design alternatives are given in Figure 5. In design A, only vertical rails were used between modules. Module fixings were acieved by roof hooks attached to the battens. Initially, vertical module joints were sealed by rubber seals between overlapping modules and horizontal module joints were drained by drainage channels in vertical rail profiles. Design B differs with its horizontal module joints from design A. These joints in design B were sealed with rubber gaskets clamped continuously to supporting rails. Each of design A and B have clapboard roof surface appearance by lapping modules over each other. This overlapping of modules may also help self-cleaning of module surface. In design C, only vertical rails were used with one difference. They were placed beneath the modules. Module fixings were achieved by clamps to these vertical rails. Therefore vertical and horizontal module joints werearranged as open and a waterproofing corrugated sheet is used underneath support rails. Ventilation rate is better in this design alternative due to its open module joints. This alternative has plain roof appareance. In addition, disassemby is easy for this alternative due to its point module fixings (clamps). Modules can be individually disassembled from each other. On the other hand, PV modules do not provide water impermeability in this alternative. In design D, horizontal and vertical rails were used. Horizontal rails were placed on the vertical rails. Module fixing was achieved by placing modules in horizontal rails. Module joints were sealed with rubber gaskets clamped to rails. This design has clapboard roof surface. In design E vertical and horizontal rails were arranged in the same plane. Rubber gaskets were used for module fixing to rails and for module joints' impermeability. Material consumption of design D and E is over than other alternatives due to both vertical and horizontal rail use.

1.4 Conclusion

Energy policy in Turkey should be based on energy savings and renewable sources to build an energy efficient future. Building surfaces should not be considered only as an envelope conserving energy, but also as an electricity generator. The power generation by PV is still expensive compared with conventional power generation methods. However replacing building materials with PV modules can at least partially offset the cost of building materials. In addition, the reduction of installing cost can be expected. Therefore PV modules integrated with building are effective for cost reduction. Additionally, integration of PV in roofs provide the protection of the system components against weather effects than attached systems, since the components (cables, connection boxes) stay inside the roof system. Furthermore, as a roof covering material PV have longer life-span (20-30 years) and need less maintenance than other conventional roof coverings.

Currently, financial supports are not sufficient to achieve BIPV projects in Turkey. Recent progresses regarding UNFCCC and Kyoto Protocol are expected to affect government policies about renewable energy usage. Power generation from renewable sources is expected to be supported by funds and the insufficient feed in-tariff to renewable energy production is also expected to be increased. These improvements in Turkey are important not only about environmental aspects but also to lessen dependence on importing electricity. Initially, it is suggested that the focus should be on public facilities, where they have the potential for widespread application, such as local government buildings, schools, universities, museums, technical centres, resort buildings, train station buildings, etc. In addition, the mass housing administration shall primarily analyze the possibilities of using solar energy in mass housing projects. When these improvements will be achieved in Turkey, the architects will then be confronted with the challenge of designing correct PV roof systems. Therefore in this paper, a model for the design of PV integrated steep roof systems was proposed and the model was applied for Istanbul as a case study. 5 alternative roof systems were designed with standard PV modules partially integrated in a steep roof system. Their visual impacts, ventilation rates, material consumption rates, self cleaning rates and ease of disassembly are also discussed. The model is considered to be a guide for the architects, constructors and roof covering material producers to assist in the constructional design of suitable steep PV integrated roof system alternatives.

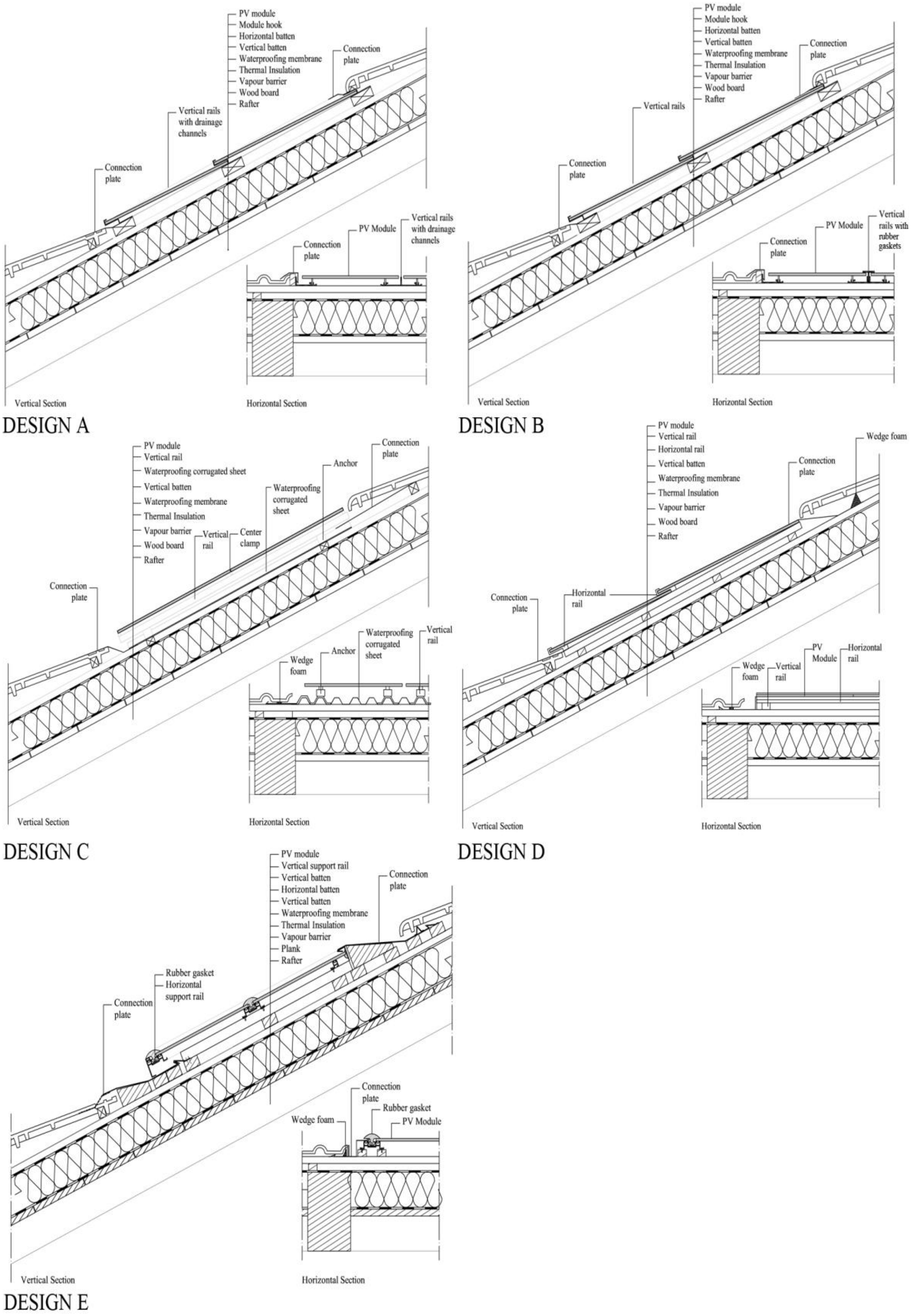

Figure 5: Design alternatives for PV integrated step roof systems for Istanbul, Turkey

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