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A Techno-Economic Analysis of Photovoltaic System Design as Specifically Applied to Commercial Buildings in Ireland

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A techno-economic analysis of photovoltaic system design as specifically applied to commercial buildings in Ireland

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Abstract

This paper evaluates the viability of installing photovoltaic (PV) systems in existing commercial buildings in Dublin. Data collected from previously installed photovoltaic systems at the Dublin Institute of Technology was analysed in order to determine the potential solar resource available in Ireland. A 1.1 kW_p photovoltaic system installed in Dublin can produce over 900 kWh of electricity in a given year depending on the available solar resource for that year. A feasibility study was conducted in Dublin city centre in order to evaluate the technical, financial and environmental aspects of integrating a PV system into an existing building. The intention is that the results from this work will help in demonstrating the benefits and challenges associated with installing PV systems in existing commercial buildings in Ireland.

Key Words:

Photovoltaic (PV), Commercial Buildings, Solar Resource Ireland.

1.Introduction

Photovoltaic (PV) electricity generation is a proven, commercially available technology. Despite its potential to contribute to Ireland's goal of generating 20% of electricity from Renewable Energy Sources (RES), in a recent study including 15 European Union (EU) countries, Ireland was ranked among the bottom users of solar energy in the EU (Celika, Clarke, Muneer, 2009). By developing viable renewable energy supply and efficient policies, the country can achieve sustainable economic growth by increasing the penetration of renewable technologies into the grid. Ireland has significant solar energy potential and on a clear day the sunlight power density can reach 940 W/m^2 (IET, 2008). Hence, it is a viable solution to aid in Ireland's achievement of the EU 20-20-20 target, particularly contributing to the 20% generation of electricity from renewable energy sources (SEAI, 2007). Due to its net carbon neutrality, it could also play a key role in displacing the use of indigenous fuels such as peat for electricity generation and in reducing the country's CO_2 emissions without compromising the energy security of supply (Foster, Ghassemi, Cota, 2010).

2. Data analysis

The utilisation factor, the ratio of energy produced to that which could potentially be produced if the plant operated uninterruptedly at full capacity, is a means of measuring the performance of the plant. Compared to conventional energy sources, solar power faces strong limitations related to unreliability and intermittence, making the utilisation factor significantly lower (Da Rosa, 2009). It is important to know the solar resource to facilitate the proper sizing and equipment selection for a PV power plant. Data from two systems previously installed in Dublin was analysed, and in combination with a simulation carried out with RETScreen software, an estimation of the solar resource in Dublin city centre and its proximity was established.

2.1 The FOCAS building installation

A 1.72 kW_p PV system was installed on the rooftop of the FOCAS building on Camden Row. It consisted of eight modules covering an area of 10 m^2 installed at approximately 12m above the ground, at a 53º inclination and at an approximate latitude of 53.33ºN (Ayompe, Duffy, McCormack, Conlon, 2011). The system was connected to a Sunnyboy 1700 inverter, a Sunny SensorBox used to measure in-plane radiation on the PV modules, various sensors at the back of the modules to measure ambient temperature, the modules' temperature and wind speed, as well as a Sunny WebBox to transfer the data to a main server to be stored.

The data selected for this analysis was the global radiation on the horizontal (at 0°). The solar radiation sensor had ± 8% accuracy and a resolution of 1 W/m^2. The data was extracted from the server in raw form, and it consisted of 36 text files each containing approximately 8000 lines of data. The information was organised by hourly average per month per year for a three-year interval

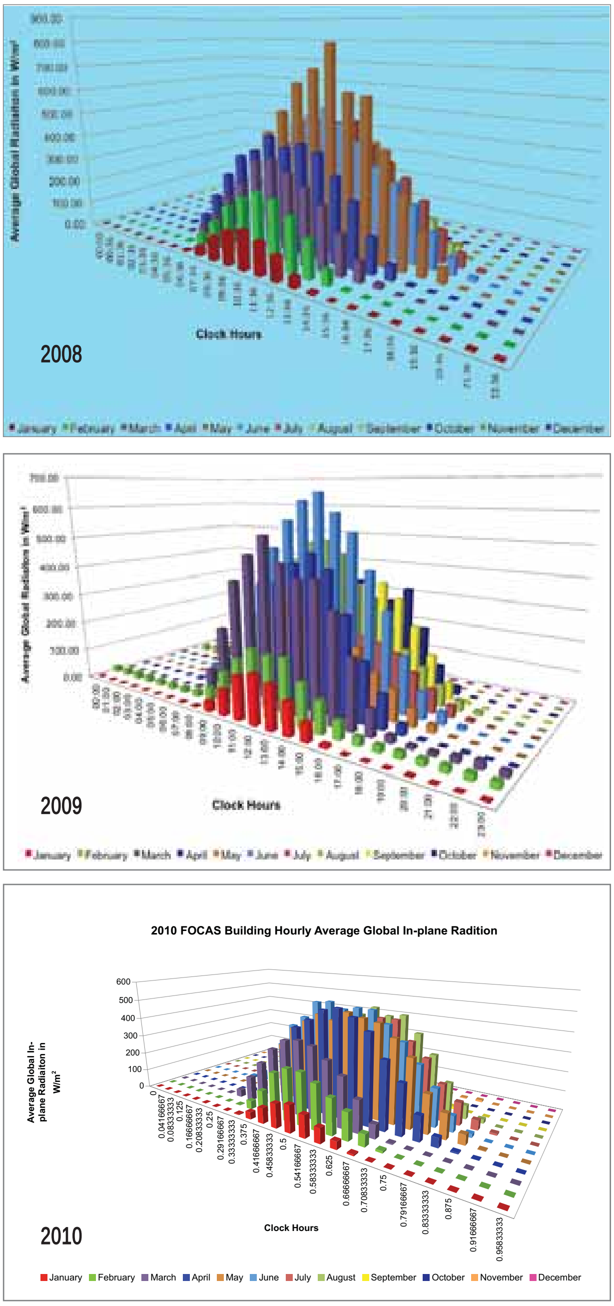

Figure 1. FOCAS Building hourly average global in-plane radiation (W/m²) for 2008, 2009 and 2010.

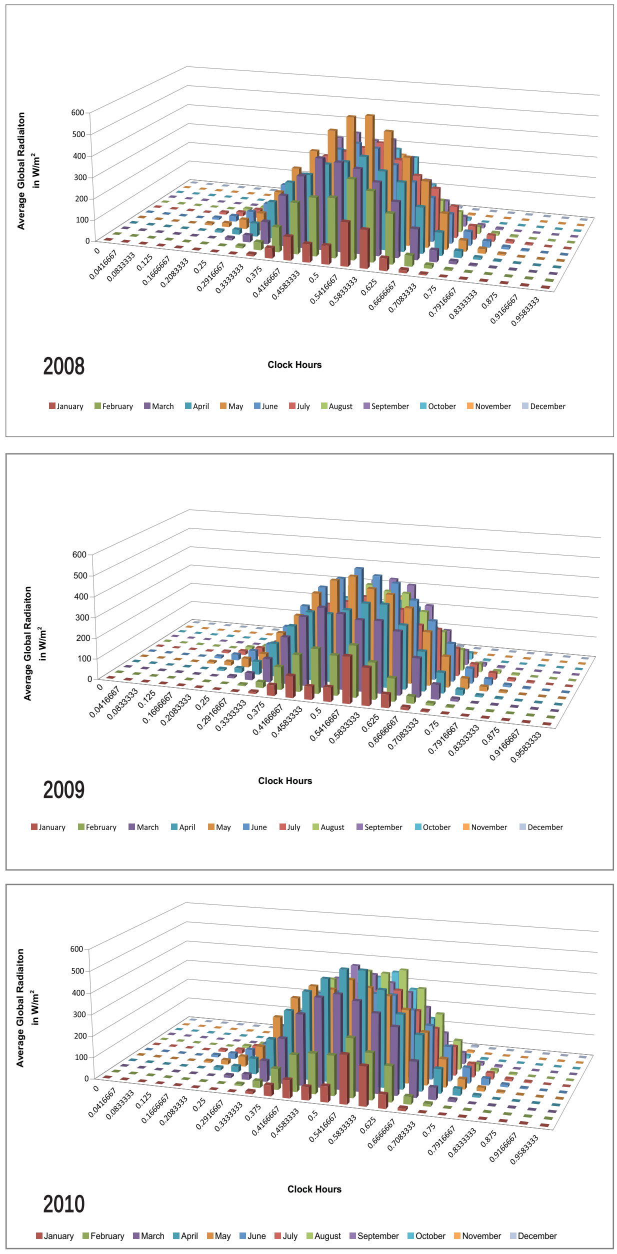

Figure 2. Church Lane Building hourly average global in-plane radiation (W/m²) for 2008, 2009 and 2010.

commencing in 2008 (Fig 1). Under overcast conditions, the radiation was extremely low or practically nil, hence the values were reported as negative values. For the purpose of this study, all negative values were taken as equal to zero.

The data revealed that the highest level of insolation experienced during the 3-year period was 807 W/m² at 12:00 hours in May 2008. Literature indicates that typically the highest insolation level is experienced during the summer months (May, June, July and August) (Foster, et al. 2010). The data showed that on average 208 W/m² of radiation can be experienced in Dublin during the summer months, and 664 W/m² average peak insolation can be expected.

2.2 The Church Lane installation

The 1 kW$_p$ system installed on the south-facing facade of the Church Lane building next to the DIT Kevin Street annex building consisted of five M230-96 GET AK 210 W$_p$ modules connected in parallel and installed at a 53° ± 1° angle. The system was connected to an SMA Sunny Boy 1100 LV low voltage inverter placed inside the building. A temperature sensor was connected to the back of the middle panel to monitor the system temperature. A temperature sensor was set up to measure the ambient temperature, and an irradiation temperature sensor installed at a 53° angle to the horizontal was installed to measure the irradiation at the site (Kearney, 2010). All the sensor readings were then recorded into a main computer on site.

Four years of radiation data at an angle of inclination of 53° has been collected for the PV system installed in Church Lane. For the purpose of this analysis, the same time interval used for the FOCAS building analysis (2008-2010) was selected (Fig 2). The data was obtained in the form of 36 excel files containing over 1000 lines of data. The data was presented in W/m^2 so no conversions were necessary. The highest level of insolation was 588 W/m^2 at 13:00 hours in May 2008. The highest levels of insolation for each year were recorded on the same month as the FOCAS building data. The 2008 and 2009 insolation levels were significantly lower for the Church Lane installation than for the FOCAS building.

2.3 RETScreen data simulation

RETScreen is an analysis software that facilitates feasibility analysis for RES, such as PV systems (CETC, 2005). One of its main features is the weather database. The software utilises the data from the closest airport, in this case Dublin Airport, to estimate the amount of insolation available for Dublin. Dublin Airport is located at 53.42° N and at 6.25° W. This is approximately the same latitude and longitude at which both systems discussed previously are located; hence similar radiation levels were expected. The simulation results showed the highest level of insolation was experienced in July, with an average of 4.72 kWh/m^2/d or approximately 197 W/m^2. The average global radiation for the summer months was 4.3 kWh/m^2/d, which equates to 179 W/m^2. The average daily global radiation in a year was 2.53 kWh/m^2/d, or approximately 925 kWh/m^2 per year based on 365 days in a year.

2.4 Analysis of solar resource

The measured data would have provided more precise results if a larger time interval had been utilised. It can also be misleading in terms of sizing and designing the overall PV system. The data from the two systems, on a clear day, did not vary significantly between hourly averages. However on partly cloudy days, larger fluctuations existed between one hour and the next. If the system was designed based solely on this 3-year period data, its true performance could be underestimated, as in future years, there might not be similar overcast conditions (Beckman, Klein, Kummert, Vijayakumar, 2005). This is a significant consideration for the Irish climate. Ideally, a high quality global irradiation meter should have been installed at each site to collect data for a longer period of time. However, these were not available.

The global radiation result differences between the FOCAS and Church Lane buildings are interesting, as the radiation levels should have been practically the same considering their proximity in location. This can be attributed to the solar radiation data being measured at different angles of inclination. The FOCAS building sensor measured the radiation on the horizontal while the Church Lane measured it at a 53° angle of inclination. Previous research has indicated that larger levels of radiation are received on horizontal surfaces, particularly during summer months. However, in regions that experience cloudiness and are farthest away from the equator, larger overall amounts of insolation are received on inclined surfaces throughout the entire year (Mondol, Norton, Smyth, Yohanisa, 2006).

The RETScreen software only provides data on global radiation on the horizontal. However, the results seem to be a midpoint between data collected from both installations. The information is statistically more accurate as it is based on data collected over a large period of time at an actual weather station, with precise equipment dedicated to providing meteorological information. For the purpose of this project, the RETScreen results were assumed as the most accurate source available. These results were used in the case study. However, the results from the two installations were still considered for sizing and designing the PV system.

3. VHI House feasability study

A feasibility study was conducted at the VHI House in Dublin city centre to explore the benefits and challenges associated with PV technology in the commercial sector in Ireland. The study focused on evaluating the usage of a PV system to meet some of the base load of the building. The use of PV for thermal generation was not considered. The roof area available for the PV system installation was approximately 184 m^2, and there were no trees or tall buildings that could potentially provide shading or obstruction to the system. Approximately 375 people occupied the building, and it was open to staff Monday to Friday from 6:00 to 19:00; Saturday from 6:00 to 12:00; and closed on Sundays.

The site's electrical profile was constructed by averaging the loads from June 2010 to May 2011 on an hourly average basis per month, and on an overall monthly average basis. The load was relatively consistent throughout the year, and a data centre operates on 24/7 schedule. The total annual electrical consumption for 2010 was 2,678,304 kWh, which equates approximately to 458 kWh/m^2 per year. The building's high summer loads were a great fit for a PV installation, as the greatest amount of energy output recorded for PV devices in Ireland has been in summer months (Kazmerski, 2006).

The solar resource was estimated using the data presented in Section 1. It was concluded that the average daily global radiation available in Dublin is 2.53 kWh/m^2/d, or approximately 925 kWh/m^2 per year based on 365 days per year. The highest insolation level was recorded in 2008 at the FOCAS building at a value of 807 W/m^2.

3.1 The System

The modules for the PV generator were selected based on IEC 61215:1993: Crystalline Silicon Terrestrial Photovoltaic (PV) modules – Design, qualification and type approval, the SOLAREC (2009) list of approved PV panels, the CIBSE Guide TM25 Understanding Photovoltaic Systems, and the SEAI (2011a) Accelerated Capital Allowance (ACA) 2011 approved list of product (CIBSE, 2000, IEA, 2009). The Sharp NU-E235 module with a 235 W_p output, conversion efficiency of 14.3% and an area of 1.65 m^2 was selected (Sharp, 2011). It was calculated that 80 modules could fit on the roof area. The building was located at 53°N, hence the ideal angle of inclination for the modules was 53°. The modules would be installed at an inclination of 53° facing south, with and optimum length of separation of 778 mm from the back of the first module to the next module as determined by means of angle calculations (Beckman, Duffie, 2006).

The manufacturer's specifications stated that each module had a maximum output power under Standard Test Conditions (STC) of

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235.2 W. Using data from the Sharp technical data sheet and assuming a maximum insolation value of 807 W/m^2, the maximum point voltage and current were calculated to be approximately 27.5 V and 7.056 A respectively, resulting in 176.4 W_p. Using the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) data, the resulting peak power (W_p) per cell was 211.5 W_p. At a maximum irradiance of 807 W/m^2 the panel's temperature would be 50°C, experiencing an approximate 10% decline in voltage. Hence, the expected power output would be reduced to 190 W_p (Clinckaert, 2006).

Assuming the calculated value of 176.4 W_p, a cell efficiency of 14.3%, insolation of 807. W_p/m^2 and 133 m^2 of roof area available, the PV generator could produce approximately 19.285 MWh/yr. This would represent 0.7% of the building's load. It must be noted that this does not account for the balance of the system losses.

Relying on I.S. EN 50530:2010 overall efficiency of grid connected photovoltaic inverters, the ACA grant 2011 approved list of products, and data from previous installations in Ireland, a SMA inverter was selected (Ayompe et al., 2011; SEAI, 2010a; SEAI, 2011b). The maximum rated inverter on the list was 8 kWp, however based on the calculations the system was expected to output 14.4 kWp. According to the manufacturer's specifications, the maximum inverter efficiency of 96% is achieved when the PV generator produces 246 V. The inverter's efficiency curve demonstrated that even if the PV system produced low power, i.e. anything over 12.5W or 5% output power, the efficiency of the inverter would still be above 90% (SMA, 2011). This was ideal for the proposed installation due to the expected large insolation variation throughout the year, and low power output from the PV generator during the winter. Three-6kW Sunny Mini Central 6000A would be connected to the 5 PV sections.

The PV module connection configuration was determined after various iterations. The chosen configuration is shown in Figure 3. This configuration allowed for overall system efficiency and the ability to add on to the system if required with the inverters L1, L2 and L3 being fused at 40A. The remaining BOS components were also determined. Each PV string would be connected by 35mm^2 RZ cables composed of electrolytic copper with non-halogen insulation and fireproof cover to minimise voltage drop, maximise mechanical protection and reduce any further losses such as those associated with an increase in cable temperature. Each component in the Balance of System (BOS) would be individually isolated as per ET 101:2008 (ETCI, 2008).

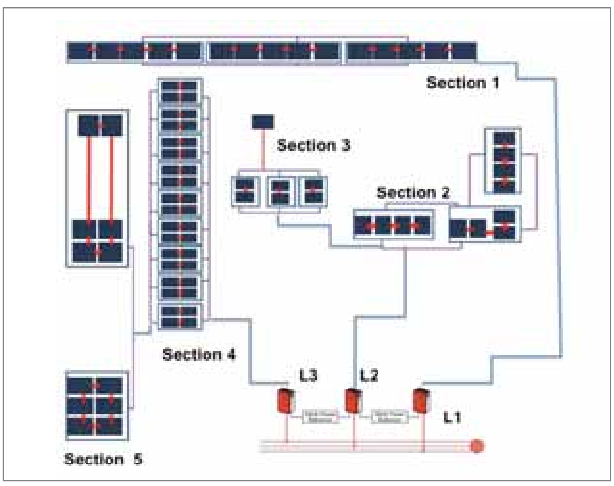

Figure 3. Schematic of PV generator connection configuration (SMA, 2011).

Table 1. Project Cost for the 3 Scenarios

Scenario	Initial Cost (€)	Total Annual Cost (€)	Grant/ Incentive (€)	Annual Electricity Cost (€)	Total Annual Fuel Cost Saving (€)
No Grants	94,426	352,212	0	354,443	2,231
BEW	94,426	352,212	40,000	354, 443	2,231
ACA	94,426	352,212	7,700	354, 443	2,231

A system simulation was conducted using RETScreen software. The software database did not contain the Sharp 235NU modules; however a similar module, Heliene 235 Wp, with the same specifications was utilised. The results indicated the PV system could produce approximately 17.598 MWh/yr. Manual calculations proposed 19.285 MWh/yr of DC output power, and AC output power of 17.935 MWh/yr (based on inverter efficiency of 96% and 3% cable losses). Both results seemed fairly close; however the RETScreen results were taken as most accurate since the software calculations were based on a greater solar resource database.

3.2 Financial evaluation

The economic feasibility of the installation of any renewable energy system depends on two critical values – the capital cost of the hardware and installation, and the amount of energy produced annually (Kalogirou, 2009). For faster investment payback, the maximum amount of energy should be used on site. The capital costs are relatively high for PV, however the fuel cost is non-existent (Foster, et al., 2010). Hence, if grants or incentives are available, the initial cost or capital cost of investment in the system will be reduced, making the installation more viable. In Ireland the Better Energy Workplaces (BEW) scheme provides grants starting at €20,000 up to €500,000. For the purpose of the calculation, the value of the grant was taken as €40,000 (SEAI, 2011b). The Accelerated Capital Allowance (ACA) scheme is geared towards companies paying corporate tax. For practical matters, the building was considered eligible; corporate tax was taken at 12.5%, and a 100% write-off the value of the system was assumed (SEAI, 2011a).

Cash flows without grants and with grants were calculated using RETScreen, and the cost of PV produced energy was also calculated manually. The following financial parameters were used for both calculations: Fuel cost escalation rate (5%), inflation rate (1.4%), discount rate (6%) and project life (30 years). The fuel cost escalation rate was based on natural gas reports (Ireland's primary fuel for electricity) from the ICE (2011) index and the IEA (2009). Inflation rate was taken from the most recent report produced by the Central Bank of Ireland (CBI, 2010), and the discount rate and project life were based on other projects installed in Europe. The project cost for each scheme is depicted in Table 1.

The main items considered for capital cost were: the development and engineering, and the PV system (modules and the BOS). The annual costs of running the system were estimated at around €100, as the system would require very little maintenance due to its stationary nature. The system was estimated to produce 0.7% of the building's electrical requirements, therefore purchase cost of additional electricity for the building was assumed to be at €0.13/kWh (current price charged to the building by the Electricity supplier). The simulation demonstrated that the *no grant* scenario would have a 22-year payback period. The BWE grant scenario had a payback period of 15 years assuming €40,000 grant. The ACA scheme provided a tax relief of €7,700 based on an investment of €61,400 at 12.5% corporate tax rate (Fig 4).

The cost of energy was calculated for the three schemes using the following equation:

$$C_{Electricity} = \frac{C_{Annual}}{E_{Produced}}$$

The results are displayed in Table 2. If the BEW grant value was larger, or if it were possible to combine the BEW and the ACA schemes, the capital cost and the cost per kWh produced could be reduced.

3.3 Environmental evaluation

Environmental evaluations are based on material and energy flows, ignoring external costs and risks related to water and land use, fuel depletion, energy security and fuel mining, transportation, usage and disposal accidents (Kearney, 2007). The system proposed was composed of mono-crystalline wafers. The life cycle of CO_2 emissions for electricity generation by mono crystalline silicon PV systems, including the manufacturing and construction of the components, is 5.020 $kgCO^2/kW_p$, which equates to approximately 0.0055 tCO_2/kW_p. This would mean that the proposed 18.8 kWp system would have life cycle CO_2 emissions of 0.1034 tCO_2.

In 2010, the building consumed 2,702,542 kWh of electricity. Based on the utility company's data, this equated to approximately 1,506 tCO_2. The Building Energy Rating certificate completed in 2011 reported the building produced 150 $kgCO_2/m^2/yr$. Typically, a building like this should offset 100 tCO_2 or less Greenhouse Gases (GHG) (SEAI, 2011b). Based on the RETScreen environmental analysis, the gross annual GHG emissions reduction was estimated to be 9.6 tCO_2. This is approximately equivalent to the emissions produced by two cars or a light truck. The RETScreen software assumes 0% emissions produced by the PV system, as it does not take into consideration the energy spent in manufacturing and supply chain for the components. This is due to the fact that it is quite low, 0.1034 $tCO_2$2, hence it is assumed to be insignificant. The values proposed by the simulation were taken as the most accurate results, as these values were based on a larger number of databases compiled for over more than 30 years (CETC, 2005).

3.4 Case study conclusions and recommendations

The study presented the requirements for the feasibility of installing a PV system on a commercial building. It was demonstrated that less than 1% of the building's electrical load was generated by the installation. From a financial perspective, the Better Energy Workplaces scheme was the most favourable scheme. However, the cost of energy is still expensive compared to the current cost of €0.13/kWh paid for electricity. It would be recommendable to explore the use of solar thermal systems to contribute to the building's thermal load. According to a study published by the SEAI, the capital cost per solar collector for largescale solar thermal plant would be around €250 to €310. This would equate to approximately 8.44 €cents/kWh (SEAI, 2010). This option could be quite viable, when compared to the current cost of natural gas, 5 €cent/kWh.

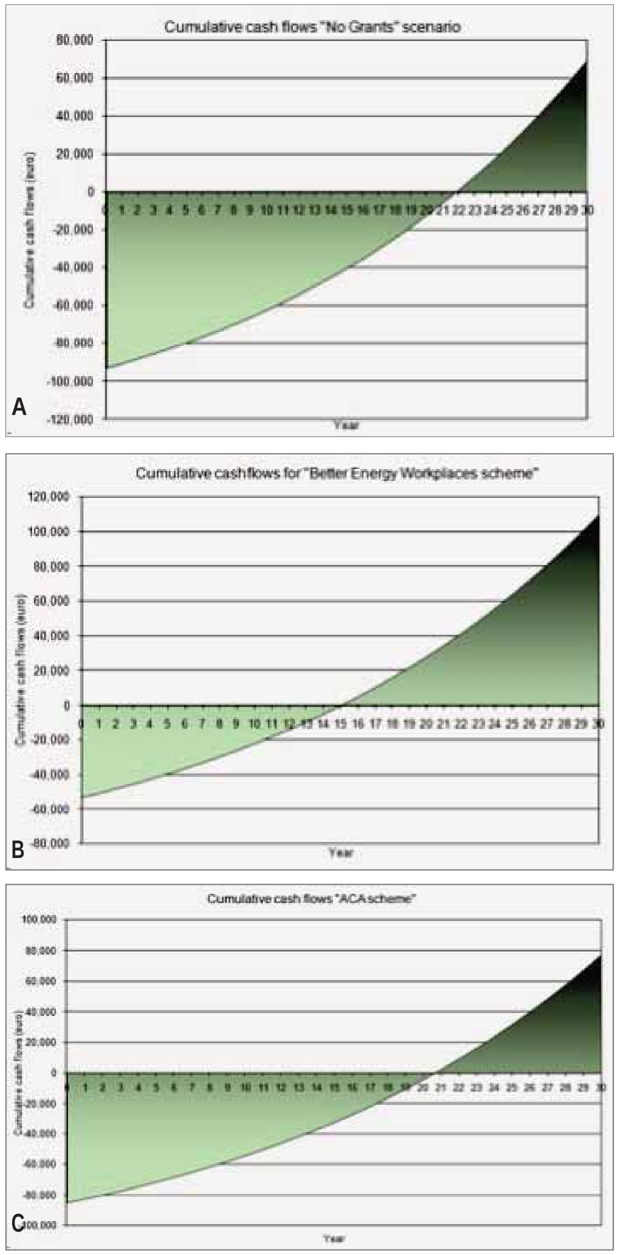

Figure 4. Cash Flow for (a) No Grants Scenario, (b) BEW scheme and (c) ACA scheme.

4. General conclusions

Based on the FOCAS and Church Lane systems, the average daily global radiation that is available in Dublin was 2.53 $kWh/m^2/d$, or approximately 925 kWh/m2 per year based on 365 days per year.

Table 2. Cost of Energy for the 3 Scenarios

Scenario	Capital Cost (€)	Discount Rate (%)	Project Life Time (N)	Annual Cost (€)	Elect. Prod. (kWh)	Elect. Cost (€kWh)
No Grant	94,426	6%	30	6,860	17,598	€0.39
BEW	54,426	6%	30	3,954	17,598	€0.22
ACA	86,726	6%	30	6,301	17,598	€0.36

The highest insolation level was recorded in 2008 at the FOCAS building at a value of 807 W/m^2. Most inverters are designed to achieve maximum efficiency (between 90-95%) at 50% of the nominal DC power they receive. Inverters are capable of tracking the PV generator's MPP in order to maximise the PV system's efficiency.

Based on the feasibility, it is not financially viable to design PV systems to meet the entire electrical demand of buildings with excessively large electrical requirements. The minimum payback period for the PV installation based on current costs of equipment and the grants and incentives available in the country would be 15 years. If no grants or incentives are available, it will take over 20 years before the system starts to produce a profit.

5. Future research

A study should be conducted to evaluate how different commercially-available PV technologies perform under the Irish climate conditions. The solar resource data used in this study was collected from systems utilising monocrystalline modules, and simulation results were based on monocrystalline modules. It would be interesting to explore the utilisation of multijunction PV cells, and the efficiency benefits they could provide in Ireland. Further research into Building Integrated PV should be carried out in Ireland. It would be of particular interest to conduct studies that would combine the retrofitting of the building envelope, the use of passive building design, and the integration of PV technology. This would provide a holistic approach, and more realistic results for the implementation of PV technologies in existing commercial buildings.

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