Projected Costs of a Grid-Connected Domestic PV System Under Different Scenarios in Ireland, Using Measured Data from a Trial Installation

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Projected costs of a grid-connected domestic PV system under different scenarios in Ireland, using measured data from a trial installation

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Abstract

This paper presents results of a study of projected costs for a grid-connected PV system for domestic application in Ireland. The study is based on results from a 1.72 kWp PV system installed on a flat rooftop in Dublin, Ireland. During its first year of operation a total of 885.1 kWh/kWp of electricity was generated with a performance ratio of 81.5%. The scenarios employed in this study consider: a range of capital costs; cost dynamics based on a PV module learning rate of 20 ± 5%; projections for global annual installed PV capacity under an advanced and moderate market growth conditions; domestic electricity cost growth of 4.5% based on historic data; and a reduction of 25% or 50% in the CO2 intensity of national electricity production by 2055. These scenarios are used to predict when system life cycle production costs fall to grid prices (grid parity).

Average NPV and electricity generation costs ranged from −€14,330 and 0.58 €/kWh and were close to zero and 0.18 €/kWh for a system installed in 2009 and 2030, respectively. However, under optimistic conditions NPVs are positive for systems installed after 2021 and grid parity occurs in 2016. Findings are compared with similar international studies.

1. Introduction

In April 2008, the Irish Government indicated its interest in micro-generation by announcing the implementation of a micro- and small-scale electricity generation programme. Pilot trials were due to be installed in 2009 for domestic scale PV systems (Sustainable Energy Ireland, 2008b). Furthermore, in February 2009 the Irish Government and the largest Irish electricity supplier, the Electricity Supply Board (ESB) introduced a feed-in tariff of 19e cents per kWh for electricity from micro-generation (Department of Environment Heritage and Local Government, 2009). In order to evaluate the performance of PV systems in Ireland it is imperative that both field trials which provide information on the annual energy yield of typical installations as well as studies to determine the economics and environmental benefits of PV systems be undertaken. This information is necessary for evidence-based policy design and implementation. During operation, PV systems generate electricity without the emission of greenhouse gases such as CO2, while displacing electricity generated from conventional power plants. The adoption of PV systems offers significant benefits to household in terms of reduced energy bills and to society as a whole in terms of reduced greenhouse gas emissions (Ren et al., 2009). Numerous issues remain still to be resolved if PV micro-generation is to be implemented on a large-scale within the residential sector. Some of these issues include: high electricity generation costs; high capital cost, high CO2 abatement costs; lack of an adequate tariff structure for electricity sale; grid integration; and load profile mismatch with electricity generation.

The main objective of this paper is to provide an insight into the projected energy, economic and environmental performance of PV systems for domestic applications in Ireland based on system cost, system performance, solar radiation data, CO2 emission and energy output dynamics. This would provide useful information to potential investors and policy makers.

2. Methodology

Performance results of a 1.72 kWp PV system installed in Dublin, Ireland were used to determine the annual performance ratio and total in-plane solar insolation which are important parameters used to determine annual energy generation. The total energy generated throughout the PV system’s life of 25 years was...
Table 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module price</td>
<td>€2009/kWp</td>
<td>Cm</td>
<td>5700 ± 1100</td>
</tr>
<tr>
<td>BOS cost factor</td>
<td>%</td>
<td>km</td>
<td>54</td>
</tr>
<tr>
<td>BOS replacement cost factor</td>
<td>%</td>
<td>kR</td>
<td>70</td>
</tr>
<tr>
<td>BOS component life time</td>
<td>Year</td>
<td>Nc</td>
<td>10</td>
</tr>
<tr>
<td>Interest rate</td>
<td>%</td>
<td>i</td>
<td>5</td>
</tr>
<tr>
<td>Discount rate</td>
<td>%</td>
<td>d</td>
<td>5</td>
</tr>
<tr>
<td>Variable cost factor</td>
<td>%</td>
<td>kV</td>
<td>1</td>
</tr>
<tr>
<td>Peak power</td>
<td>kWp</td>
<td>Ppeak</td>
<td>1.72</td>
</tr>
<tr>
<td>Global radiation</td>
<td>kW/h/m²/yr</td>
<td>G</td>
<td>1035</td>
</tr>
<tr>
<td>Standard radiation</td>
<td>kW/m²</td>
<td>Isc</td>
<td>1</td>
</tr>
<tr>
<td>Annual degradation of energy yield</td>
<td>%</td>
<td>s</td>
<td>0.82%</td>
</tr>
<tr>
<td>Performance ratio</td>
<td>%</td>
<td>Q</td>
<td>80.8</td>
</tr>
<tr>
<td>Base year electricity export price (feed-in tariff)</td>
<td>€2009/kWh</td>
<td>P_{el,im}</td>
<td>0.16</td>
</tr>
<tr>
<td>Base year grid supplied electricity price</td>
<td>€2009/kWh</td>
<td>P_{el,im}</td>
<td>0.16</td>
</tr>
<tr>
<td>Annual growth rate of grid supplied electricity price</td>
<td>% (€2009)</td>
<td>r_{im}</td>
<td>4.5</td>
</tr>
<tr>
<td>Annual growth rate of feed-in tariff</td>
<td>% (€2009)</td>
<td>r_{ex}</td>
<td>0</td>
</tr>
<tr>
<td>PV system life time</td>
<td>Years</td>
<td>N</td>
<td>25</td>
</tr>
<tr>
<td>Percentage of on-site electricity use</td>
<td>%</td>
<td>Eim</td>
<td>96</td>
</tr>
</tbody>
</table>

Estimated taking into consideration an annual output drop as a result of module degradation as a result of exposure to ultraviolet radiation. A PV system life of 25 years was chosen in this study since it is same as the performance warranty period of many module producers (EPIA, 2008).

The average installed cost of PV systems in Ireland in 2009, a learning rate of 20 ± 5% and two scenarios for PV system annual installed capacity growth were used to project the system’s installed cost until 2030. These projected costs together with the economic parameters in Table 1 were used to calculate projected net present value and the life cycle cost of electricity generation for different years of installation at which the PV system is installed.

Net life cycle greenhouse gas (GHG) emissions were calculated taking into consideration two scenarios reflecting different trends in the GHG intensity of electricity production in Ireland. The net life cycle GHG emissions were used to evaluate GHG abatement costs associated with PV generated electricity in different years of installation.

Key assumptions:
- The current feed-in tariff is applicable throughout the PV system’s life.
- CO₂ emissions due to embodied energy can be ignored from a national emissions policy perspective since PV modules and system components are not manufactured in Ireland.
- The inverter is replaced after 10 years.

3. PV system performance

3.1. System description

The grid connected photovoltaic system used in this study was installed at the rooftop of the Focas Institute building, Dublin Institute of Technology, Ireland. It consisted of 8 modules covering a total area of 10 m² with an installed capacity of 1.72 kWp. The Sanyo HIP-215NHE5 modules were each of 215 Wp capacity and comprised 72 solar cells made of thin mono-crystalline silicon wafer surrounded by ultra-thin amorphous silicon layers. The modules had an efficiency of 17.2% under standard test conditions and were connected in series. The unshaded modules were fixed, inclined at an angle of 53° equal to the latitude of Dublin, facing south at an azimuth angle of zero degrees. The PV modules were not cleaned throughout the monitoring period. A single phase Sunny Boy SB 1700 inverter was used to convert DC to AC which was fed directly into the building. The inverter had a maximum efficiency of 93.5% and maximum AC power of 1700 W. In-plane total solar radiation was measured using a Sunny SensorBox. Additional sensors for measuring ambient temperature, wind speed and temperature at the back of one of the PV modules were connected to the SensorBox. The solar radiation sensor had an accuracy of ±8% and a resolution of 1 W/m². The PV module temperature sensor was a PT100-M type with accuracy of ±0.5 °C while the ambient temperature sensor was a JUMO PT 100 U type with accuracy of ±0.5 °C. The anemometer was a Thies small wind transmitter with accuracy of ±5%. Fig. 1 shows the PV modules and inverter installation.

3.2. Solar radiation and performance ratio

The PV system was monitored between November 2008 and October 2009. Fig. 2 shows variation of monthly average daily total in-plane long-term solar insolation for Dublin, performance ratio and total in-plane solar insolation over the monitored period. A horizontal surface in Dublin receives on average 920 peak sunshine hours annually. Long-term monthly average daily total in-plane 53° solar insolation values were obtained using RetScreen4 software (RetScreen International, 2009). The PV system’s annual performance ratio was 81.5% while the annual total in-plane solar insolation over the monitored period and the long-term annual average for Dublin were 1043 and 1034 kWh/m², respectively. The annual total in-plane solar insolation over the monitored period was 0.83% higher than the long-term average so the corrected long-term performance ratio of 80.8% was used in this study.

3.3. PV system cost

The installed cost of a roof mounted, grid-connected PV system depends on its capacity; type of PV modules; nature of the building on which it is to be installed; cost of balance of system (BOS) components and installation cost. A survey of 16 crystalline PV systems installed under the government pilot trial programme administered by Sustainable Energy Ireland in 2009 with capacities between 1–6 kWp was conducted. Results showed that...
the average installed PV system cost including value added tax was $8750 \pm 1700$ €/kWp with BOS accounting for 30–40%. In this study 35% was chosen as the average BOS cost factor of the PV system. The average PV module cost was $5700 \pm 1100$ €/kWp with BOS accounting for 54% of this cost. An economic analysis was conducted using three PV module costs notably $4600$, $5700$ and $6800$ €/kWp. BOS of a PV system consists of all the systems or engineering components apart from the PV modules or cells. It primarily consists of an inverter to transform the direct current (DC) output from the PV array into a form of alternating current (AC) electricity that can be synchronized with and connected to the electric utility grid. It also involves support structures and all the cost of labour involved in system installation (Shum and Watanabe, 2008).

Despite an impressive growth in annual PV installation in Europe, Ireland still lags with virtually little or no installations. In 2008, the cumulative installed PV capacity in Ireland was 0.4 MWp made up of 0.1 and 0.3 MWp of grid-connected and off-grid capacity, respectively. The installed photovoltaic power per inhabitant in Ireland was 0.09 Wp/inhabitant while the EU 27 average was 19.2 Wp/inhabitant (Eurobserv’er, 2009). The small PV market size in Ireland indicates why PV system prices are relatively higher than those in other countries with more established markets such as Germany, Spain and Italy.

In order to take into account cost dynamics of the PV system, experience curve analysis was used. The concept of learning-by-doing expresses that accumulating the deployment or use of a technology increases the corresponding experience, which typically results in the optimization of the process involved. In particular, technology improvements are often economic in nature and thus result in cost reductions, so that changes in cost or price are usually used as a proxy for learning-by-doing (Ferioli et al., 2009). Learning curves are usually expressed as (van der Zwaan and Rabl, 2003; Bhandari and Stadler, 2009; Ferioli et al., 2009)

$$C(x_t) = C(x_0)(x_t / x_0)^b$$

where $x_t$ is the cumulative installed PV module capacity at year $t$; $b$ the learning parameter or learning elasticity parameter or rate of innovation; $C(x_t)$ the PV module cost per kWp at year $t$; $C(x_0)$ the PV module cost at an arbitrary starting year; $x_0$ the cumulative installed PV module capacity at an arbitrary starting point.

Learning curves are derived by fitting Eq. (1) to cost and production data observed in the past. The starting point then ideally corresponds to the first unit of production. In practice, however, it often proves more appropriate to choose a later (but still early) stage of deployment for $t=0$, and for the purpose of estimating future cost reductions on the basis of learning curves, it can be convenient to use the present cumulative production as starting point (Ferioli et al., 2009).

The learning rate (LR) is defined as the relative cost reduction (in %) after each doubling of cumulative production, and is given...
as Ferioli et al. (2009)

\[ LR = 1 - 2^b \quad (2) \]

With every doubling of cumulative production, costs decrease to a value expressed as the initial cost multiplied by a factor called the progress ratio. The progress ratio (PR) is given as (van der Zwaan and Rabl, 2003; Bhandari and Stadler, 2009).

\[ PR = 1 - LR = 2^b = 2^{\frac{\ln(C_0)}{\ln(2)}} \quad (3) \]

Learning at PV module level makes no distinction between global and local learning, since most of the module manufacturing is done by internationally operating companies and there is extensive exchange of scientific and technological information on module technology (Bhandari and Stadler, 2009). Shum and Watanabe (2008) argue that BOS learning is mostly local in nature while module learning is relatively global. Therefore, BOS learning can mostly be attributed to cumulative experience of system design, integration and installation attained through greater system integration and a reduction in the number of BOS parts.

A learning rate of 20% with a sensitivity range of ±5% that accounts for uncertainties of PV technologies and cost development as recommended by Neij (2008) was used in this study. Future PV module costs were evaluated using learning rates of 15% and 25% (progress ratio of 0.85 and 0.75, respectively). In order to extrapolate future costs of PV modules, it is important to estimate future global installation of PV systems.

Global PV electricity generating technology has sustained an impressive annual growth rate compared with other renewable energy generating technologies. Total global installed capacity of grid-connected PV systems was 3.5, 5.1, 7.5 and 13 GWp in 2005, 2006, 2007 and 2008, respectively (Renewable Energy Policy Framework, 2009). EPIA (2008) developed an advanced and a moderate scenario for future growth in global installed PV capacity. The advanced scenario is based on the assumption that continued and additional market support mechanisms will lead to a dynamic expansion of worldwide PV installed capacity. Under this scenario, average growth rates of 40%, 28% and 18% were proposed for the periods of 2007–2010, 2011–2020 and 2021–2030, respectively. On the other hand, the moderate scenario envisions the development of PV against the background of a lower level of political commitment. Average growth rates of 30%, 21% and 12% were proposed for the same periods, respectively. Annual installed PV capacity would therefore be 2.4, 6.9, 56 and 281 GWp for the advanced scenario and 2.4, 5.3, 35 and 105 GWp for the moderate scenario in 2007, 2010, 2020 and 2030, respectively.

Figs. 3 and 4 show projected values for global annual installed PV capacity and costs for the moderate and advanced scenarios, respectively. The two scenarios were used to estimate future costs of PV modules until 2030. Under the moderate scenario, the cost of PV modules per kWp drops from €4600, €5700 and €6800 in 2009 to €2058, €2550 and €3042, respectively, for a learning rate of 15% and to €1108, €1373 and €1638, respectively, for a learning rate of 25% in 2030. Under the advanced scenario, the cost of PV modules per kWp drops from €4600, €5700 and €6800 in 2009 to €1687, €2091 and €2494, respectively, for a learning rate of 15% and to €779, €966 and €1152, respectively, for a learning rate of 25% in 2030.

3.4. Electricity cost trend

Electricity domestic general rate in Ireland increased from 9.5e cents/kWh in 1989 to 18.1e cents/kWh in October 2008 and then dropped to 16.0e cents/kWh in 2009 (Sustainable Energy Ireland, 2008a). This represented an annual average escalation of 0.43e cents/kWh (4.5%). However, a linear best fit trend on the electricity general domestic rate data from 1989 to 2009 gives the projected cost shown in Fig. 5.

3.5. Economic analysis

The economic analysis presented in this paper assumes that it would be economically viable to invest in a grid connected PV system when the net present value is positive. The net present value (NPV) is the sum of discounted single and annual cash flows over the service life of the PV system less the initial capital cost. It is an indicator of the PV system’s worth, with a positive value signifying that benefits accrued will exceed costs over its economic life. The higher the NPV, the greater the financial benefit with an NPV greater than zero indicating a profitable investment (Rogers, 2001; Twidell and Weir, 2006).

This study is based on PV system performance, solar radiation and market data for Dublin, Ireland. Values used in the analysis
are shown in Table 1. The PV used in this analysis had a capacity of 1.72 kWp and generated 885.1 kWh/kWp during its first year of operation. The average annual electricity consumption of a representative domestic dwelling in Ireland is 5591 kWh. An analysis run on the daily energy generated by the PV system on 15 min interval and the energy demand profile for the representative dwelling revealed that over a year, 96% of the energy generated will be consumed on-site while 4% will be exported to the grid. Over the lifespan of the PV modules, exposure to ultraviolet radiation would lead to degradation of power output. A study conducted by Osterwald et al. (2002) showed a linear dependence of maximum power degradation of 0.82% per year for mono-crystalline Si modules due to exposure to ultraviolet radiation.

3.5.1. Performance ratio

The performance ratio (Q) indicates the overall effect of losses on a PV array’s normal power output depending on array temperature and incomplete utilization of incident solar radiation and system component inefficiencies or failures. The PR of a PV system indicates how close it approaches ideal performance during real operation and allows comparison of PV systems independent of location, tilt angle, orientation and their nominal rated power capacity (Blaesser, 1997). Performance ratio is defined by the following equations as (Eicker, 2003; Nakagami et al., 2003):

$$Q = \frac{\eta_{sys}}{\eta_{STC}} = \frac{E_{AC}}{G_t} \frac{G_{STC}}{E_{DC,STC}}$$ (4)

where, $\eta_{sys}$ is the system efficiency (%); $\eta_{STC}$ the efficiency under standard test conditions (%); $E_{AC}$ the AC energy output (kWh); $E_{DC,STC}$ the DC energy output under standard test conditions (kWh); $G_t$ the total in-plane solar radiation; $G_{STC}$ the total solar radiation under standard test conditions.

3.5.2. Net present value

The present value of total cost of the PV system is the sum of the present value of costs associated with the PV module, initial BOS, replacement cost of BOS and variable cost. It is assumed that
money used to buy the PV modules and BOS components are obtained from a bank loan. The total life cycle cost of the PV system \( (C_t) \) is given as \( C_t = C_{int} + C_{BOS} + C_{BOSrep} + C_v \) and written as

\[
C_t = C_{peak} P_{peak} \left[ \sum_{n=1}^{N} \frac{1+i(N-n+1)}{N(1+d)^n} \right] + \left\{ \sum_{n=1}^{N} k_{BOS} (1+i)^N n (1+d)^N \right\} + k_v (1+k_{BOS}) \sum_{n=1}^{N} \frac{1}{N(1+d)^n}
\]  

The PV module price reduction factor \( (k) \) is given as

\[
k = C_{m(n+N)} / C_{m(n)}
\]

where \( C_t \) is the total PV system cost (€); \( C_{int} \) the present value of cost associated with PV module \( (€_{2009}) \); \( C_{BOS} \) the present value of cost associated with the initial investment on BOS \( (€_{2009}) \); \( C_{BOSrep} \) the present value of BOS replacement cost \( (€_{2009}) \); \( C_v \) the present value of total variable cost \( (€_{2009}) \); GHG EF the greenhouse gas emission factor.

The present value of total revenue from the system during its useful life is the sum of the present value of revenue of PV generated electricity consumed on-site and the present value of revenue of electricity exported to the grid. The size of the PV system and the electricity demand profile determine the quantity of electricity it generates that is used on-site to displace grid supplied electricity at a cost of \( P_{el,im} \) for a given year. The present value of total revenue \( (R_t) \) of the PV system is given as

\[
R_t = P_{peak} Q_{STC} \sum_{n=1}^{N} \frac{1}{N(1+d)^n} + P_{el,im} E_{on} \sum_{n=1}^{N} \frac{(1+n r_{im})(1-s)^n}{(1+d)^n}
\]

The net present value (NPV) of the PV system is given as

\[
NPV = R_t - C_t
\]

3.5.3. PV electricity cost

The cost of electricity generated \( (C_e) \) in €/kWh is the ratio of the life cycle cost of the PV system to the total power output from the PV system over its service life and is given as

\[
C_e = \frac{C_t}{E_n}
\]

The total power output \( (E_n) \) in kWh by the PV system over its service life is given as

\[
E_n = P_{peak} Q_{STC} \sum_{n=1}^{N} (1-s)^n
\]

3.6. Greenhouse gas emission analysis

CO2 emissions associated with electricity generation in Ireland dropped from 0.728 kg CO2/kWh in 2005 to 0.644 kg CO2/kWh in 2006 and then 0.538 kg CO2/kWh in 2007 with the introduction of the All-Island Single Electricity Market. This drop in CO2 emissions was as a result of fuel switching from coal, oil and peat to gas and renewables. In 2007, electricity generation in Ireland was based on coal (18%), gas (55%), oil (6%), peat (6%), renewables (11%) and combined heat and power (4%) (Electricity Supply Board. Annual Report, 2007). This fuel mix shows that there is still potential for CO2 emission reduction in electricity generation. In order to investigate the effect of decarbonizing electricity generation in Ireland, two scenarios for CO2 emissions...
reduction were considered in this study namely: 25% and 50% reduction of 2007 emissions between 2007 and 2055 when a PV system with a service life of 25 years installed in 2030 will be decommissioned as shown in Fig. 6.

Table 2 shows the parameters used to calculate the quantity of avoided CO2 emissions by the PV system. Avoided CO2 emissions associated with grid supplied electricity are essentially those displaced by PV generated electricity used on-site. On the other hand, avoided CO2 emissions associated with PV generated electricity exported to the grid are reduced by the distribution losses on the low voltage distribution lines since this electricity ends up within the PV system’s neighbourhood.

### 3.6.1. Avoided greenhouse gas emissions

PV systems produce electricity in a CO2 neutral way during their service life although some CO2 emissions arise during the production of PV modules and other equipment. In this study the embodied emissions due to the production of the PV system components are neglected since the components are not manufactured in Ireland and do not therefore affect national CO2 emission figures. The total quantity of avoided greenhouse gas emissions (GHG avoided in kg CO2/kWh) during the PV system’s service life is the sum of avoided emissions due to the quantity of displaced grid-supplied electricity by the PV system used on-site (including transmission and distribution losses) plus the quantity of avoided emissions due to electricity exported to the low voltage distribution lines.
voltage grid (including distribution losses). It is calculated using Eq. (11) given as

\[
G_{\text{GHG avoided}} = P_{\text{peak}} \frac{G_m}{I_{\text{STC}}} \prod_{n=1}^{N} (1-s)^{-1} \frac{G_{\text{EF,n}}}{E_{\text{on}}(1+L_{\text{grid,TD}})} + (1-E_{\text{on}})(1+L_{\text{grid,TD}}-L_{\text{PV,D}})
\]

3.6.2. Greenhouse gas emissions abatement cost
The total cost of greenhouse gas emissions abatement \(C_{\text{GHG}}\) is calculated using the negative values of NPV which indicate the amount of money required to make the investment on the PV system economically viable. It is calculated using Eq. (12) given as

\[
C_{\text{GHG}} = \frac{\text{NPV}}{G_{\text{GHG avoided}}}
\]

4. Results and discussion
Four scenarios were developed to model the effect of PV module cost reduction based on a moderate and advanced growth in annual installed global PV capacity and a learning rate of either 15% or 25% (i.e. 20% ± 5%). The scenarios are illustrated in Fig. 7.

System NPVs and life cycle electricity generation costs were calculated for the four scenarios based on the PV system costs and a system lifespan of 25 years.

4.1. PV system installed in 2009
Fig. 8 shows system NPVs and electricity generation costs against PV module costs under the different scenarios for PV systems installed in 2009. It can be seen that NPVs decrease with PV module costs for a given scenario. The values in brackets represent the life cycle costs of electricity generation in €/kWh.
Electricity generation costs also decrease with increases in learning rates for a given PV module price. However, electricity generation costs which increase with PV module cost are lower for the advanced scenarios than the moderate scenarios while holding learning rates constant.

The system’s NPV reduces from €10,173 per kWp to €18,718 per kWp for the Advanced 25 and Moderate 15 scenarios, respectively. The negative NPVs showed that investment in the PV system in 2009 was not economically viable. The average cost of PV electricity generation was 0.47, 0.58 and 0.70 €/kWh for PV module costs of €4600, €5700 and €6800 per kWp, respectively.

4.2. Net present value and electricity cost projections

The negative NPV values for the PV system installed in 2009 presented in Section 4.1 show that at present it is not economically viable to invest in the PV system under the conditions assumed in this study. However, the cost reduction potential of PV modules due to market growth, learning by doing and technological developments (resulting in a learning rate of 20% per annum) together with the likely long-term increase in the value of electricity assumed to be (4.5% per annum) has the effect of improving the NPV for systems installed post 2009. Therefore, the future values of NPV and life cycle electricity generation costs for systems installed after 2009 were calculated for each of the scenarios (see Fig. 7) and capital cost projections (see Figs. 3 and 4). Results obtained show that the NPV increases with year of investment and systems become economically viable under some scenarios and PV module costs within the time horizon analysed (up to 2030). The negative values of NPV indicate the level of additional capital support required to make investment in the PV system economically viable. The support required decreases as the year of investment increases beyond 2009.

![Fig. 12. PV-generated and grid-supplied electricity cost against year of installation under different scenarios for PV module cost of €4600 per kWp.](image1)

![Fig. 13. PV-generated and grid-supplied electricity cost against year of installation under different scenarios for PV module cost of €5700 per kWp.](image2)
4.2.1. Net present value

Figs. 9–11 show variation in NPV against year of installation under different scenarios for initial (2009) PV module costs of £4600, £5700 and £6800 per kWp, respectively. Fig. 9 shows that for an initial PV module cost of £4600 per kWp, the investment would be economically viable under the Advanced 15, Moderate 25 and Advanced 25 scenarios in 2030, 2023 and 2021, respectively. Fig. 10 shows that for an initial PV module cost of £5700 per kWp, the investment would be economically viable under the Moderate 25 and Advanced 25 scenarios in 2026 and 2023, respectively. Fig. 11 shows that for an initial PV module cost of £6800 per kWp, the investment would be economically viable under the Moderate 25 and Advanced 25 scenarios in 2029 and 2024, respectively.

4.2.2. Electricity cost

Figs. 12–14 show variations in PV-generated and grid-supplied electricity costs against year of installation under different scenarios for PV module costs of £4600, £5700 and £6800 per kWp. Fig. 12 shows that for an initial PV module cost of £4600 per kWp, the life cycle cost of PV generated electricity drops from between 0.46 and 0.49 £/kWh in 2009 to between 0.08 and 0.27 £/kWh in 2030. Grid parity is projected to occur in 2026, 2023, 2018 and 2016 for the Moderate 15, Advanced 15, Moderate 25 and Advanced 25 scenarios, respectively.

Fig. 13 shows that for an initial PV module cost of £5700 per kWp, the life cycle cost of PV generated electricity drops from between 0.57 and 0.60 £/kWh in 2009 to between 0.10 and 0.27 £/kWh in 2030. Grid parity is projected to occur in 2028, 2024, 2019 and 2017 for the Moderate 15, Advanced 15, Moderate 25 and Advanced 25 scenarios, respectively.

Fig. 14 shows that for an initial PV module cost of £6800 per kWp, the life cycle cost of PV generated electricity drops from between 0.67 and 0.72 £/kWh in 2009 to between 0.11 and 0.32 £/kWh in 2030. Grid parity is projected to occur in 2030, 2023 and 2021 for the Advanced 15, Moderate 25 and Advanced 25 scenarios, respectively.
4.3. Avoided greenhouse gas emissions

Fig. 15 shows avoided total life cycle CO2 emissions against year of installation for a 25% and 50% projected reduction in grid-supplied electricity emissions between 2007 and 2055. The results show a reduction in the quantity of avoided CO2 emissions due to the projected reduction in GHG emissions associated with electricity generation. It is seen that the total quantity of avoided CO2 emissions for the PV system installed in 2009 reduces from 10.4 and 9.7 tCO2/kWp for the 25% and 50% cases, respectively, to 7.8 and 6.3 tCO2/kWp if the PV system was installed in 2030. This shows that reducing the intensity of GHG emissions associated with the generation of grid supplied electricity reduces the attractiveness of PV systems in mitigating CO2 emissions.

4.4. Greenhouse gas abatement cost

Figs. 16–18 show variations in CO2 emissions abatement costs against year of installation for a 25% and 50% projected CO2 emission reduction and initial PV module costs of €4600, €5700 and €6800 per kWp. It can be seen that CO2 abatement costs decrease for all scenarios with increasing year of installation; abatement costs also decrease with decreasing PV module installation costs. In the best case, no subsidies are required from 2021 onwards.

Fig. 16 shows CO2 emissions abatement costs against year of installation for an initial PV module cost of €4600 per kWp for both a 25% and 50% reduction in the CO2 intensity of electricity production by 2055. In the case of a 25% reduction in CO2 emissions, abatement costs decrease from between €569 and 523 €/tCO2 in 2009 to between 230 and 0 €/tCO2 in 2020 and finally to between 55 and 0 €/tCO2 in 2030; costs are higher for the Moderate 15 scenario in all cases. For 50% reduction in CO2 emissions, abatement costs decrease from between 624 and 569 €/tCO2 in 2009 to between 269 and 0 €/tCO2 in 2020 and finally to between 70 and 0 €/tCO2 in 2030; again costs are highest for the Moderate 15 scenario.

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Fig. 17 shows CO₂ emissions abatement costs against year of installation for an initial PV module cost of €5700 per kWp, for both a 25% and 50% reduction in the CO₂ intensity of electricity production by 2055. In the case of a 25% reduction in CO₂ emissions, abatement costs decrease from between 759 and 897 €/tCO₂ in 2009 to between 358 and 566 €/tCO₂ in 2020 and to between 168 and 646 €/tCO₂ in 2030; costs are higher for the Moderate 15 scenario in all cases. For 50% reduction in CO₂ emissions, abatement costs decrease from between 948 and 1198 €/tCO₂ in 2009 to between 418 and 656 €/tCO₂ in 2020 and finally to between 213 and 697 €/tCO₂ in 2030; again costs are highest for the Moderate 15 scenario.

Fig. 18 shows CO₂ emissions abatement costs against year of installation for an initial PV module cost of €6800 per kWp, for both a 25% and 50% reduction in the CO₂ intensity of electricity production by 2055. In the case of a 25% reduction in CO₂ emissions, abatement costs decrease from between 948 and 1198 €/tCO₂ in 2009 to between 356 and 536 €/tCO₂ in 2020 and finally to between 213 and 697 €/tCO₂ in 2030; again costs are highest for the Moderate 15 scenario.

4.5. Comparative analysis

Table 3 shows projected costs for PV electricity generation for rooftop system in different locations (European Photovoltaic Industry Association and Green Peace 2008). Current life cycle electricity generation costs for Dublin are at least 50% higher than equivalent locations in Europe (Berlin and Paris). The disparity in electricity generation costs however decreases somewhat after 2010.

5. Conclusion

Results of a study on projected economic and environmental performance of a 1.72 kWp pilot trial rooftop mounted PV system in Dublin, Ireland has been presented. Measured performance data was used to evaluate the performance ratio and correct same using long-term solar radiation data. Measured PV output was used to dynamically evaluate the quantity of electricity generated by the PV system that would be used on-site relative to a 15 min average electricity demand profile for domestic dwellings in Ireland with annual average consumption of 5591 kWh. It was determined that 96% of the energy generated would be used on-site with only 4% available for export. Over an estimated useful service life of 25 years, an annual average of 759 kWh/kWp of electricity would be generated by the PV system with output loss due to UV degradation accounting for 9.2% of total generation assuming no losses.

An average PV module installed cost of 5700 ± 1100 €/kWp obtained from a survey of 16 systems installed in 2009 was used. A current feed-in tariff of 0.19 €/kWh was used which assumed to remain constant throughout the analysis period. Grid supplied electricity was projected to increase linearly at an annual rate of 4.5% based on 20 years of historic data. Four scenarios for PV module cost growth were developed based on PV module learning rates of 15% and 25% as well as a moderate and an advanced global PV market growth. The quantification of GHG emissions avoided and GHG abatement costs were evaluated assuming a 25% and 50% reduction in GHG emissions associated with grid-supplied electricity between 2007 and 2065. The economic and environmental performance of the PV system was evaluated for years of installation between 2009 and 2030 inclusive assuming a 25 year lifespan (with production up to 2055).
Results obtained showed that domestic grid-supplied electricity cost is projected to grow from 0.16€/kWh in 2009 to 0.27€/kWh in 2030 and 0.45€/kWh in 2065. PV generated electricity costs decrease from 0.60 and 0.57€/kWh in 2009 to 0.27 and 0.10€/kWh in 2030 for the Moderate 15 and Advanced 25 scenarios, respectively. Grid parity would then occur in 2030 and 2019 for the Moderate 15 and Advanced 25 scenarios, respectively. The system NPVs increase from –€14,926 and –€13,734 in 2009 to €2,971 and €2,731 for the Moderate 15 and Advanced 25 scenarios, respectively, during the same period. The corresponding normalized NPVs would therefore increase from –€8,678 and –7,985€/kWp in 2009 to –1,727 and 1,588€/kWp respectively. For all four scenarios considered, the average PV generated electricity costs drop from 0.18€/kWh while the average NPV increases from –€14,330 to –€35 if the PV system is installed in 2009 and 2030, respectively. The normalized average NPV increases from –8,331 to 20€/kWp for PV systems installed in 2009 and 2030, respectively. Grid parity then occurs in 2024. The total quantity of avoided CO2 emissions for the PV system installed in 2009 reduces from 10.4 and 9.7 tCO2/kWp for the 25% and 50% cases, respectively, to 7.8 and 6.3 tCO2/kWp if the PV system was installed in 2030. The life cycle cost of CO2 abatement drops from between 523 and 1030€/tCO2 in 2009 to between 0 and 356€/tCO2 in 2030.

A comparative analysis shows that current PV system costs are at least 50% higher in Ireland than other jurisdictions with similar climatic conditions. This suggests that the market is not operating optimally, possibly due to the low numbers of buyers and sellers or due to a lack of market information such as system price and quality. Significant decreases in capital costs might occur, therefore, if many buyers and sellers entered the market and information were more freely available. This would require market intervention such as subsidies (e.g. grants or low cost loans), higher feed-in tariffs, or regulation. However with a current marginal cost of abatement of between 523 and 1030€/tCO2, widespread deployment would be costly and would not represent best value for money for the taxpayer.

References


Glossary

Annual degradation of PV yield (s): Percentage at which the maximum power output of a PV module is expected to decrease due to exposure to ultraviolet radiation (%);

Balance of system (BOS): All PV system components other than the PV modules or cells;

BOS cost factor (kBOS): BOS components cost relative to the cost of PV modules; Discount rate (D): Interest rate used to discount future cash flows (%); Feed-in tariff (FIT): Policy mechanism designed to pay the producer of electricity at a specific rate usually higher than the purchase price; Global radiation (G): Sum of beam (direct) and diffuse (indirect) solar radiation (kW/m2/yr);

Greenhouse gases (GHG): Gases in the atmosphere that absorb and emit radiation within the thermal infrared range;

Grid parity: When the cost of PV generated electricity equals that of grid supplied electricity; Interest rate (I): Rate charged or paid for the use of money expressed as an annual percentage of the principal (%);

Net present value (NPV): Sum of present value of costs associated with the PV system and benefits minus the initial investment, reduced to the present with the chosen discount rate (%); Peak power (Ppwa): Maximum rated power under standard test conditions; Performance ratio (Q): Indicator of how close a PV system approaches ideal performance during real operation and allows for comparison of PV systems independent of location, tilt angle, orientation and their nominal rated power capacity; PV system life (N): Period during which a PV system produces energy (years); Standard radiation (I0): Total solar radiation under standard test conditions for PV modules (1 kW/m2); Variable cost factor (kV): Proportion of the initial investment used annually for system maintenance and insurance.