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A Techno-economical Appraisal of a PV Domestic Plant on a Irish Dwelling

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Contents

1 Introduction

Global Photovoltaic (PV) production capacity in the year 2014 was estimated to have exceeded 180GW worldwide at the end of the year [1]. Solar PV has become a mature technology and reliable commercial solutions are now available to provide competitive power in a complete range of applications.
In Ireland however the PV sector never reached a remarkable threshold. 154 PV micro-generation[1] installations was encountered at the end of 2013 for a total of 441 kW installed [2]. There are also some existing stand-alone (no grid-connected) commercial

[1]Microgeneration is classified by ESB Networks as grid connected electricity generation up to a maximum rating of 11kW when connected to the three phase portion of the distribution grid (400V). Single phase customers (230V) maximum technical rating permitted to be classified as microgenerators is 5.75kW. However ESB Networks accept applications for generators up to 6kW.

and domestic installations, but statistics are not available for these installations.
A growing interest has been mounting in Ireland in the last couple of years primarily for the dramatic fall of the cost of the PV modules. Solar PV module prices in 2014 were around 75% lower than their levels at the end of 2009. Between 2010 and 2014 the total installed costs of utility-scale PV systems have fallen by 29% to 65%, depending on the region. As a result the Levelised Cost of Electricity (LCOE) of utility-scale solar PV has fallen by half in four years between 2010 and 2014 [1].
The scope of the present study is to develop a techno-economic model of a domestic PV system from the perspective of the householder. An economic simulation was run starting from the adopted model and resulting in an evaluation of the possible investment in the year 2016.
A collection of real data from a grid connected PV system installed at the rooftop of the Focas Institute building was used to evaluate the real inputs to feed in the simulation. It consisted of 8 modules covering a total area of $10m^2$ with an installed capacity of $1.72kW_p$. The system was installed during 2009 hence it will be used to have an idea of the Annual Net Capacity Factor (ANCF)[2] to be compared with actual values from specific PV Geographical information system available online.
A selection of 334 consumers real load profiles for year 2010 were additionally used. The data are provided as power meter readings of the actual power used by each consumers every 30-minute interval. These data have been used to get an average profile of a consumer and to get a reasonable mean parameter for the on-site electricity to be used in the next simulation.

2 Techno-Economical parameters

Initially a rational analysis of the collections of data obtained must be done in order to introduce the following Section 3 with the proper inputs. The electrical energy consumption per dwelling in Ireland in 2011 was $5022kWh$ showing an average annual growth rate of 1% between 1990 and 2011 [3].
The average annual consumption of studied sample was $5928kWh$ obtained as the sum of the utilised energy every half an hour in one year given by:

$$\bar{E}_{annum}[kWh] = \sum_{i=1}^{17520} \bar{P}_{C,i}[kW] \cdot \frac{[h]}{2} \tag{1}$$

Where $\bar{P}_{C,i}$ is the mean value of the power consumption of the 334 consumers every 30 minutes and 17520 is the number of half an hour in one year, i.e. $48 \cdot 365 = 17520$.
In Figure 1 is shown the consumption profile of a single consumer in comparison with

[2]The net capacity factor of a power plant is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity continuously over the same period of time.

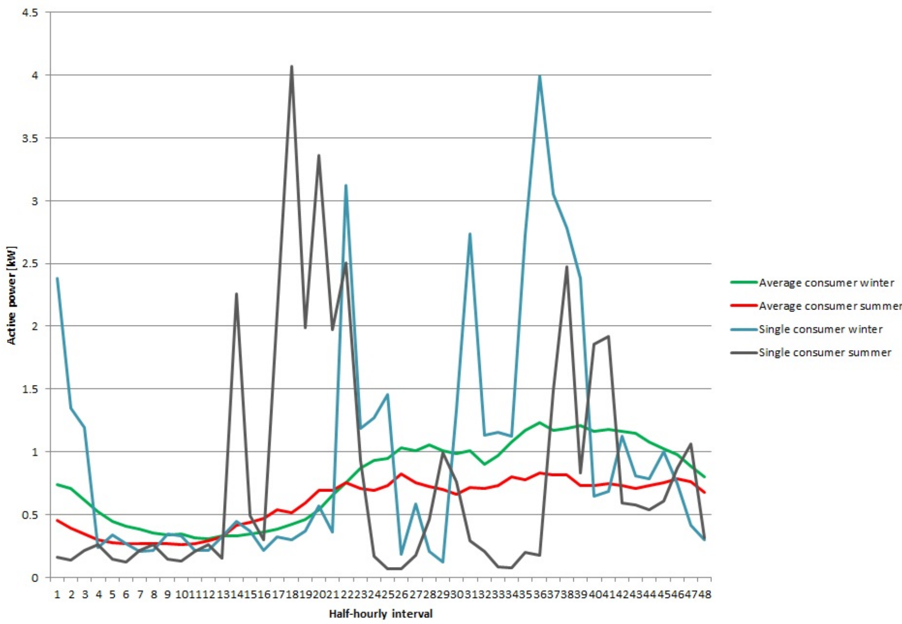

Figure 1: A comparison between the average consumption of 334 domestic consumers and a single domestic consumer on 1^{st} January and 1^{st} July

Table 1: Daily energy consumption, i.e. the area under the curves in Figure 1

	Single consumer	Average consumer
Cold season	23.8kWh	18.6kWh
Warm season	19.6kWh	14.2kWh

the average consumer. The value are given as power absorbed in kW every half an hour so the integral represents the energy consumption in kWh. Two particular days for warm and cold season were chosen to show the weather dependency of the load. 1^{st} January was chosen for cold season and 1^{st} July for the warm. The simple rectangle method was used to calculate the area under the curves obtaining values in Table 1. It is important to note that the consumption during the cold months are considerably higher than those in Summer. This is a normal consequence of the relative cold weather in the Winter and mild weather in Summer which don't require any particular air conditioning system during the warm months. On the contrary this has a considerable importance for the PV installations which naturally gives the higher output during the very long daylights in the warm season.

The second collection of data as mentioned before is the average 30-minute interval PV system power output before the inverter hence on the DC link. Although the data have been collected for a period of 2 years the considered plant is one so to get a good statistic

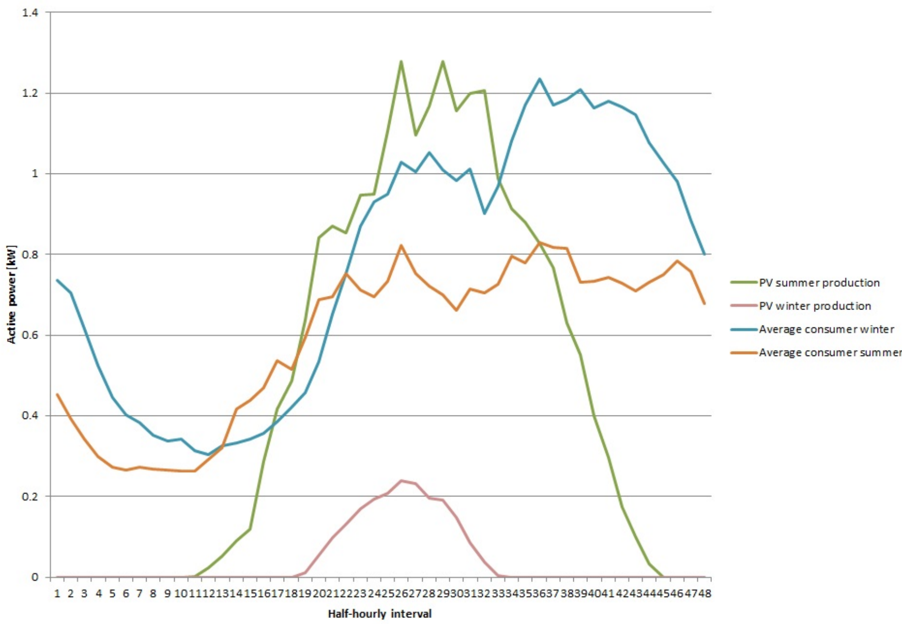

Figure 2: Average consumer load characteristic against the PV production profile of the analysed system of about $1.72kW_p$

from the data an average on the 5 days with longer daylight (around 21^{st} June) and the 5 with the shorter daylight (around 21^{st} January) were made. The obtained PV power production profiles are visible in Figure 2 where is yet reported the average consumption, for cold and warm seasons, of the 334 consumers.
It is of immediately deduction that all the energy produced during the winter is going to be used from the average consumer whereas in the summer a considerable amount of energy will be spilled in to the grid. According to ESB [4] Electric Ireland was the only supplier to have a micro-generation pilot scheme with an export payment rate of 9.0 c€ per kWh to domestic customers. However this scheme is already closed for new costumers and is going to finish at the end of 2016. This means that the value of the on-site consumption assumes a strategic importance in the definition of a PV system for domestic use.

2.1 On-site consumption and PV system size definition

Analysing Figure 2 it is possible to estimate the percentage of the on-site use of electricity of the average consumer. Obtained values are listed in column one in Table 2. With no claim of being exhaustive but a weighted sum of the two values would give the proper parameter to be used in the next economical study. The ratio between the PV production during cold months over warm ones was calculated using the PV production database

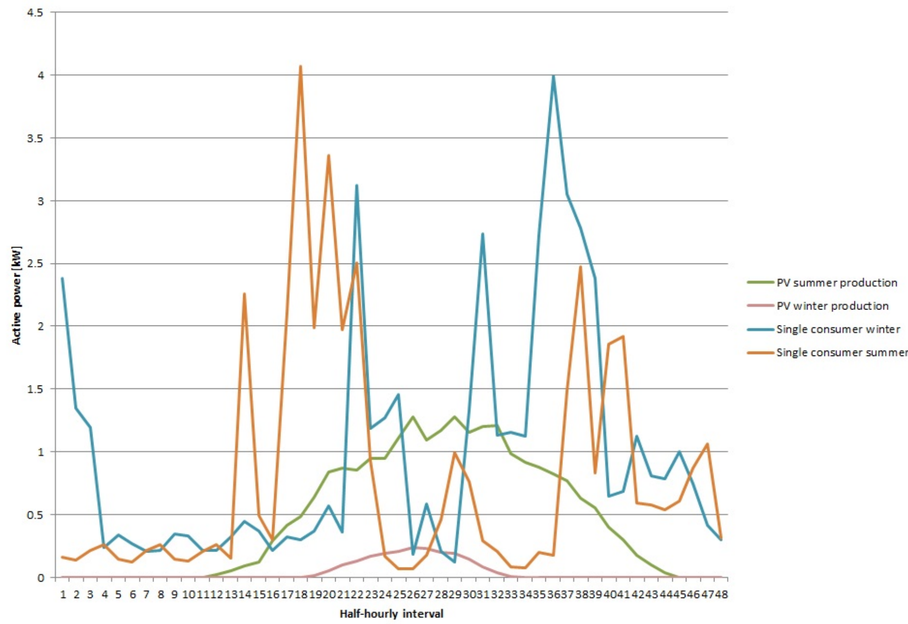

Figure 3: Single consumer load characteristic against the PV production profile

Table 2: Values of on-site electricity used pointing out the difference between the average consumer with a real single consumer

	In-house consumption for average consumer	In-house consumption for single consumer
Cold season	1	0.94
Warm season	0.77	0.52

resulting to be 23% of production during cold months and the rest 77% during warm months. Hence the weighted sum would give a good 82.5% of on-site consumption.
Unfortunately as shown in Figure 1 the difference between the load characteristic of the single consumer and the average consumer is noteworthy. For convenience of viewing a comparison between the single load characteristic with the PV system production is reported in Figure 3. Many household electrical appliances indeed work much less than half an hour and with strong absorption values, prime examples are electric showers and kettle but many others can be cited as toaster, microwave or hoover. Therefore the on-site consumption for single consumer has been calculated considering curves in Figure 3 and the result values can be found on the second column in Table 2. Again making the 77/23 weighted sum on the warm/cold months a value of 61.5% can be obtained.
A consideration on the size of the PV system analysed here must be done in order not to miss the benefits of a deserved optimization on the proportion of the plant. The size

Table 3: Estimate for a domestic PV plant in Ireland in 2016 [7], price excludes VAT and it is ex-works in Dublin

Item	Quantity
Eging Mono 285W	12
Solis Single Phase 3.6kw Dual Input	1
Mounting rail 3.2m Black	4
Mounting Rail 3m Silver	4
Mounting Rail Joiner	8
End clamp Black	8
Middle clamp Black	20
Mounting Rail End Caps Black	4
Tile Roof hook	36
Flashing Kit for Plain Tiled Roofs	36
MC4 Solar Connector	2
4mm Solar Cable 25m Length - Plain	1
AC 10A - KG 10 T203/GBA270	1
DC 20A - KG 20 T104/D-P003	0
Label Sheet	1
Kit Price	€4280.37

of the considered PV installation of about $1.72kW$ was chosen as a result of constraint reasoning. To find a suitable value for domestic users a glance at a more mature PV market must be given.

At the end of 2014 Italy had in operation $18609MW$ of PV systems which produced $22306GWh$ [5] on an overall consumption of $291084GWh$ [6]. The average installation value is not at disposal but over the 90% of the installed PV systems are in the range $3 < P <= 20kW$ [5]. A remarkable difference on the size of the domestic consumption must be bear in mind, notoriously the southern Europe countries consume much less electricity than north European mostly because of the climate. Hence for the Irish market installing a bigger plant is a benefit that can be directly assumed, naturally if the roof layout allows the installation. The main reason is that the bigger a PV system is the less incidence of the installation cost will affect the overnight cost. Additionally a pro and a cons are well visible from Figure 3 if we imagine to expand the PV production for instance redouble it. On one hand the PV production profile will include much more energy used by the consumer itself but on the other the energy spilled to the grid will increase much more resulting in an overall decrease of the on-site energy used.

All mentioned reasons affected the system dimension choice and the on-site consumption parameter adopted. For the PV system size the stated before dimensions on the Italian market and the bigger consumption of the Irish domestic energy market was taken into consideration. An estimate was asked to an Irish online company supplier for a PV kit

complete of PV modules, mono-phase inverter, mounting rails, hooks, clamps, cables and breakers, see details in Table3. The array consists of 12 modules covering a total area of $19.6m^2$ with an installed capacity of $3.42kW_p$. The Eging EGM60-C modules were each of $285W_p$ capacity and comprised 60 cells made of mono-crystalline silicon wafer. The module has an efficiency of 17.4% under standard test conditions. An important parameter is nowadays almost a standard offered by the suppliers and it is a guarantee warranty period with respect to power output. The Eging mono crystalline module has a 3.5% degradation in the first year and 0.68% per year thereafter, ending at 80.18% in the 25^{th} year after date of delivery.
The on-site consumption parameter adopted in the next economical analyses wants to take into consideration a desirable positive change in the quantity of electricity on-site consumed by the consumers, or better called a prosumer. The on-site consumption was hence increased from the 61.5% calculated above to a desirable 70%.

2.2 Annual Net Capacity Factor

As discussed above in Section 1 the PV production database was used in order to get the ANCF. This is a very important value for the economical analysis and it gives the possibility to compare the real obtained value with the production forecast from official geographical database.
Adding the annual produced energy by the studied PV plant on the rooftop of the Focas building and dividing the sum for the theoretical annual energy production gives the ANCF. The factor can be indeed obtained from:

$$ANCF = \frac{1}{2} \cdot \frac{\sum_{i=1}^{17520} P_{P,i}}{365 \cdot 24 \cdot 1720} \cdot \eta_{inv} \qquad (2)$$

Where $P_{P,i}$ is the power produced by the analysed PV system in the $i-th$ half an hour, 1720 is the peak power value of the same plant and η_{inv} is the inverter efficiency that is maximum 93.5% for the installed mono-phase inverter, a SunnyBoy 1700.
The efficiency of an inverter is maximum when it works at the rated power, in this case $1700W$. Unfortunately the PV system works almost all the time well below this power level. For this reason it is commonly used η_{EU}[3] a standard weighted efficiency parameter. The SunnyBoy 1700 inverter used has an $\eta_{EU} = 91.8\%$.
Using equation 2 and the above discussed efficiency parameter year 2009 gave an ANCF value of 9.6% and 2010 of 9.8%.
A rational comparison with the data provided by the JRC Photovoltaic Geographical Information System [8] should be done at this point. To obtain the same ANCF average value of 9.7% at the latitude of Dublin with an array orientation of 53° and an azimuth

[3]The "European Efficiency" is an averaged operating efficiency over a yearly power distribution corresponding to middle-Europe climate proposed by the Joint Research Center (JRC), based on the Ispra climate (Italy), and is now referenced on almost any inverter datasheet, calculated as:
$\eta_{EU} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.1 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.2 \cdot \eta_{100\%}$

of 0° it must be taken into account an overall losses value, due to the inverter and cables, of 20%. This value, much bigger than expected, tells that in the analysed system there are other important losses over the inverter losses.
Naturally the actual inverters on the market have efficiency values much better than that inverters at disposal 7-8 years ago. For example the Solis Single Phase chosen on the estimate has of $\eta_{EU} = 96.4\%$. Hence it is possible to estimate a reasonable value of losses to calculate an updated value of ANCF at Dublin latitude. Using the JRC geographical database with an assumed value of 12% of other losses (including cables and inverters) an annual average electricity production of $985 \frac{kWh}{kW_p}$ gives an ANCF of 11.24%. Value which will be used in next Section 3.

3 Economic Analysis

Technical parameters to be used in this section have been discusses profoundly in previous Section 2. In order to make an economical analysis for a domestic consumer other economical parameters are needed at this point.
The initial investment cost must consider Value Added Tax (VAT), transport and installation cost. VAT is 23% in Ireland whereas other costs can differ from place to place. Renting a VAN can be an optimal solution for 1 day and 100 € seems a reasonable price. On the other hand the installation cost can be very variable from dwelling to dwelling hence an assumption it is needed. Based on the experience on the Italian market an average value of 1000€ can be a reasonable price. These values bring the total capital investment cost to be 6364.86€ at year 0.
Operation and Maintenance for a domestic PV installation are low and mostly related to the cleaning of the rooftop and some clamp replacements. An initial cost of 80€ was therefore used. Although an estimate year life of 25 years for the Solis inverter is given the warranty is 5+5 years. Hence at the 13^{th} year a prevision of inverter replacement was envisaged at an actual cost of 800€ VAT included.
Another essential value for the economic study is the energy price at year 0. All the savings will be calculated starting from a price of 22.89 c€/kWh, a prudent average price for a domestic consumer of about $6000 kWh/annum$.
For O&M costs and cost of electricity at year 0, the proper sector Index of Consumer Prices (ICP) must be used on the provision of 25 years of operation. ICP index has become very tricky in the last decade but the European Central Bank (ECB)s Governing Council has announced a quantitative definition of price stability [9]: "Price stability is defined as a year-on-year increase in the Harmonised Index of Consumer Prices for the euro area of below 2%." Even if the index is actually well below this threshold on a long term analyses is better to take the ECB target hence 2% was used for O&M costs.
Sometimes the price indexes excludes energy products because these usually rise in price much higher than other components. This is a real benefit for the proposed simulation, insofar the savings will increase by the time. The Energy component of the ICP has

been therefore chosen to be 3%.

Discount Rate The Discount Rate (DR) deserves a particular emphasis because of the high impact on the whole economic study. DRs are often estimated on the basis of the Weighted Average Cost of Capital (WACC). Substantially the WACC sizes the opportunity cost of making an investment, i.e. the return that could have been earned on an alternative investments with similar risks. The WACC is a forward-looking approach, reflecting the risk inherent in future cash flows, but it is typically calculated using historical prices. An interesting report [10] prepared for the Committee on Climate Change (UK) try to identify and assess the main drivers of discount rates for low-carbon generation projects, taking into account both technological and market risks. In the 2011 the current discount rate (real value) for Solar PV installation was in the range $6-9\%$ and it was foresaw that the investors' risk perceptions will be affected by the government support for low-carbon technologies and by the improvements in the technology maturity. Based on this assumptions a value of 6.5% was chosen in the next study.

3.1 Simulation

In a case of a domestic PV installation two prospects may occur. First the consumer has in his own equity the amount necessary for the PV system. Such an amount would be invested in this particular expenditure instead of another feasible choice, whence the importance of the concept of the discount rate.
The second option would be to borrow a percentage of the necessary amount from a lender, a bank or some specialised companies. In this case the interest factor should be introduced. If the investment would be very profitable as it was in some European markets in presence of strong incentives, as Feed in Tariff, the option to get a loan would be a valuable option. In Ireland at the moment there is not an interesting National support for this kind of renewable installation so a consumer who decide to install it is very likely to have the necessary amount ready to use. For this reason with opted for the first scenario, i.e. equity used.
The PV modules warranty period for material defects and workmanship is 10 years from the date of delivery, however the warranty period with respect to power output continues for a total of 25 years from same date. To consider a business plan without any warranty for such a long time isn't free of risk, for example loss of production for a while. Anyhow home insurance sector in Ireland is well developed and so external harms such as storm damage may include the PV installation at a very low price.

Business Plan A 25 years plan is therefore simulated starting from an annual generation at year 1 of:

$$Gen_{y0} = P_{PV,peak} \cdot 8760\frac{h}{y} \cdot ANCF = 3367kWh \tag{3}$$

Where $P_{PV,peak}$ is the maximum rated power of the 12 modules adopted for a total of 3.42kW. As said year 2 sees a drop of 3.5% in the generation while a stable 0.68% degradation will bring it to 80.18% in the 25th year. Column 2 in Table 4 shows the annual generation in kWh.
The most important value from the economical point of view in a PV installation are savings on the energy bill, showed in column 3 in Table 4. They are calculated as:

$$Sav_i = Gen \cdot C_{site} \cdot c_{el,y0} \cdot (1 + ICPe)^i \tag{4}$$

As stated above the spilled electricity to the network is paid by only one energy supplier and the scheme is being renewed year by year. Spilled energy revenues are in column 4 in Table 4, as visible in the simulation a steady export payment rate $p_{sp} = 9.0$c€ was conservatively adopted for only the first 5 years.
Revenues from spilled energy are calculated as:

$$Rev = Gen \cdot (1 - C_{site}) \cdot p_{sp} \tag{5}$$

O&M cost rises yearly because of the ICP as:

$$O\&M_i = O\&M_{y0} \cdot (1 + ICP)^i \tag{6}$$

Column 6, 8, 10 and 11 represent discounted quantities, respectively discounted costs, Discount Factor (DF), "Discounted" energy generated and discounted Cash Flow (CF). The DF is the factor by which a future CF must be multiplied in order to obtain the present value. To discount a quantity Q is therefore used:

$$DQ_i = \frac{Q}{(1 + DR)^i} \tag{7}$$

Column 7 represents the cash flow as the sum of initial investment, savings, revenues from spilled energy and costs, naturally all the quantities here must not be discounted.
Present Value (PVa), shown in column 9, is the value of an expected income stream determined as of the date of valuation and it simply calculated as

$$PVa = CF \cdot DF \tag{8}$$

Last column 12 in Table 4 is the cumulative discounted cash flow.
The final row shows the sum for some quantities as the discounted costs, the present value and the discounted generated energy, these values will be used to show the results of the present appraisal for the PV installation.

3.2 Results

The sum of all the PVas, i.e. the total initial investment cost (negative value) plus all the net cash inflows at the present value, gives the first economical indicator of the

Table 4: Economical simulation results

Year	Generation [kWh]	Savings [€]	Revenue [€]	O&M [€]	D costs [€]	CF [€]	DF	PVa [€]	D Gen [kWh]	DCF [€]	Cumulative DCF [€]
0					6364.86	-6364.86	1.00	-6364.86	0		
1	3367	539.56	90.92	80.00	75.12	550.48	0.94	516.88	3162	516.88	516.88
2	3250	536.30	87.74	81.60	71.94	542.43	0.88	478.24	2865	478.24	995.13
3	3227	548.63	87.14	83.23	68.90	552.54	0.83	457.42	2672	457.42	1452.54
4	3206	561.25	86.55	84.90	65.99	562.90	0.78	437.55	2492	437.55	1890.10
5	3184	574.15	85.96	86.59	63.20	573.52	0.73	418.60	2324	418.60	2308.70
6	3162	587.35		88.33	60.53	499.03	0.69	342.00	2167	342.00	2650.70
7	3141	600.86		90.09	57.98	510.77	0.64	328.68	2021	328.68	2979.38
8	3119	614.68		91.89	55.53	522.78	0.60	315.88	1885	315.88	3295.26
9	3098	628.81		93.73	53.18	535.08	0.57	303.58	1758	303.58	3598.84
10	3077	643.27		95.61	50.93	547.67	0.53	291.76	1639	291.76	3890.60
11	3056	658.07		97.52	48.78	560.55	0.50	280.39	1529	280.39	4170.99
12	3035	673.20		99.47	46.72	573.73	0.47	269.47	1426	269.47	4440.46
13	3015	688.68		901.46	397.56	-212.78	0.44	-93.84	1329	-93.84	4346.63
14	2994	704.52		103.49	42.85	601.03	0.41	248.89	1240	248.89	4595.51
15	2974	720.72		105.56	41.04	615.16	0.39	239.19	1156	239.19	4834.70
16	2954	737.29		107.67	39.31	629.62	0.37	229.87	1078	229.87	5064.58
17	2933	754.25		109.82	37.65	644.42	0.34	220.92	1006	220.92	5285.49
18	2913	771.59		112.02	36.06	659.57	0.32	212.31	938	212.31	5497.80
19	2894	789.34		114.26	34.53	675.08	0.30	204.04	875	204.04	5701.84
20	2874	807.49		116.54	33.08	690.94	0.28	196.09	816	196.09	5897.93
21	2854	826.06		118.88	31.68	707.18	0.27	188.45	761	188.45	6086.37
22	2835	845.05		121.25	30.34	723.80	0.25	181.10	709	181.10	6267.48
23	2816	864.49		123.68	29.06	740.81	0.23	174.05	662	174.05	6441.52
24	2797	884.36		126.15	27.83	758.21	0.22	167.26	617	167.26	6608.79
25	2778	904.70		128.67	26.65	776.03	0.21	160.74	575	160.74	6769.53
Sum					7891.30			404.68	37699		

profitability of the investment, the Net Present Value (NPV). A positive NPV indeed indicates that the projected earnings generated by a project or investment exceeds the anticipated costs. Generally, an investment with a positive NPV will be a profitable one and one with a negative NPV will result in a net loss. As visible in Table 4 the NPV of the analysed installation is slightly positive.
Previous result can be reversed setting the NPV equal to 0 and solving for the DR finding the Internal Rate of Return (IRR). This result, as expected is bigger than the adopted 6.5% and equal to 7.1%.
Last column in Table 4 can be used to have another capital budgeting procedure to determine once more the profitability of a project. It gives the discounted payback period which provides the overall value of a project, giving the number of years it takes to break even from undertaking the initial expenditure. At a first sight the break even is in between the 22^{nd} and 23^{rd} years and precisely a simple calculation gives 22.6 years necessary.
With no claim of being exhaustive another broadly used parameter can be obtained from Table 4, the LCOE. It is a measure of a power source which attempts to compare different methods of electricity generation on a comparable basis. It is an economic assessment of the total discounted cost to build and operate a power-generating asset over its lifetime divided by the total energy output, again discounted at the present moment, of the asset over that lifetime. Simply dividing values on last row of Table 4, column 6 value over column 10 one, it results in a LCOE equal to 20.9c€/kWh.

4 Conclusion and future recommendations

A comprehensive study of a domestic PV installation has been addressed so far in this paper. A series of non-enthusiastic results have been achieved confirming, once more, the hard profitability of these small installations in Ireland. A somewhat different story is presented by MW-size PV installation and indeed some big plants are under project both in the UK and in Ireland.
A domestic consumer who now decide to invest on such an installation in the Irish market should be seen as an early-adopter, a dear concept for many companies which are capable to foresee the coming enlargement of their market share since when their product is still expensive. Unfortunately PV sector is now really mature and it is difficult to imagine another sensible decrease on PV system costs as it has been seen in the last decade.
The comparison between the calculated LCOE for small scale domestic installation is now proposed against the German market, the leading country for PV. In [11] it is stated that in 2013 the LCOE for small PV installations in Germany stayed in between $10 - 14c$€/kWh. Comparing the highest price of $14c$€ in the German range for year 2013, with the actual calculated in the present job for Ireland of about $21c$€, suggests not a bright future for solar in Ireland without a proper incentive scheme from the Government.

At the actual price an investment cost which in Ireland returns as revenue and savings after more than 20 years seems to suit more for a philanthropist than for an investor. Finally it is in the opinion of the author that, if a incentive scheme is under study at government level, it should be more focused on the large Offshore wind farms than in the small domestic PV installations.

Nomenclature

c_{el} Cost of Electricity

$\bar{E}_{annum}$ Average annual consumption of studied sample

$\bar{P}_{C,i}$ Mean value of the power consumption of the 334 consumers

C_{site} On-site consumption

Gen Generated energy by the estimate PV plant

$O\&M_i$ Cost for Operation and Maintenance

$P_{P,i}$ Power produced measured at the $i-th$ half an hour

$P_{PV,peak}$ Maximum rated power of a PV module

p_{sp} Export payment rate

Rev Revenue from selling of spilled energy

Sav Savings, intended as avoided expenditures

ANCF Annual Net Capacity Factor

CF Cash Flow

DF Discount Factor

DR Discount Rate

ECB European Central Bank

ICP Index of Consumer Prices

IRR Internal Rate of Return

JRC Joint Research Center

LCOE Levelised Cost of Electricity

NPV Net Present Value

PV Photovoltaic

PVa Present Value

VAT Value Added Tax

WACC Weighted Average Cost of Capital

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