

2013-09-03

Grid-Tie Arrangements for Micro-Generation Under EN50438; An Irish Evaluation

Liam Murphy

Technological University Dublin, liam.murphy@tudublin.ie

Follow this and additional works at: <https://arrow.tudublin.ie/engscheleart>



Part of the [Power and Energy Commons](#)

Recommended Citation

Murphy, L. Grid-Tie Arrangements for Micro-Generation Under EN50438; An Irish Evaluation. Power Engineering Conference (UPEC), 2013 48th International Universities Dublin. DOI: 10.1109/UPEC.2013.6715039 (IEEE)

This Conference Paper is brought to you for free and open access by the School of Electrical and Electronic Engineering at ARROW@TU Dublin. It has been accepted for inclusion in Conference papers by an authorized administrator of ARROW@TU Dublin. For more information, please contact arrow.admin@tudublin.ie, aisling.coyne@tudublin.ie.



This work is licensed under a [Creative Commons Attribution-NonCommercial-Share Alike 4.0 License](#)

Grid-Tie Arrangements for Micro-Generation Under EN50438; An Irish Evaluation

Liam Murphy

School of Electrical and Electronic Engineering
Dublin Institute of Technology, Ireland
liam.murphy@dit.ie

Abstract—This paper explores the significance of EN50438 as the standard governing the grid-connection of micro-generation to the distribution network. In the context of micro-generation, EN50438 therefore governs the inverter requirement associated with the majority of micro-generation. Another consideration presented in this research is findings and analysis related to the manufacturers stated efficiency of a grid-tied inverter connected to a Photovoltaic (PV) array in Dublin City Centre, Ireland.

Index Terms—Efficiency, EN50438, EWAE, Feed-In Tariff, Inverter, Micro-generation, MPPT

I. INTRODUCTION

Micro-generation is a technology that can offer benefit both to a Distribution Network Operator (DNO) and to the consumer from both a technical and economic perspective. Additionally, it can offer governments the opportunity to achieve a reduction in GHG's as required under the Kyoto protocol if suitable incentives are put in place for installation. The paper examines the Irish context with regard to such incentives and how they could assist the government with its commitments under the Kyoto protocol, to Europe and indeed its own previously avowed aspirations.

Micro generation integration into the Irish distribution network is at an incipient stage of development. When one looks holistically, however, at Irish policy towards renewable technologies against its European commitments [1], there have been achievements. The European Renewable Energy Directive (2009/28/EC) targeted a 16% share of renewable energy in gross final consumption by 2020. The contribution of renewable energy to overall energy demand in Ireland reached 6.5% in 2011 with a share of electricity generated from renewable energy sources being 17.6% (RES-E) [2]. This limited success should be viewed against an aspirational target of 40% set in the Strategy for Renewable Energy 2012-2020 [3].

Micro-generation has a role to play from a national and international perspective in reducing dependence on central generation and in Green House Gases (GHG) reduction strategies, but such contribution needs to be supported by Government. In 2009, the Irish Government announced a feed in tariff (FIT) of €0.19/kWh for spill energy 'exported' onto the grid; however, since April 2013 this tariff has been indefinitely suspended [4]. Currently, the only tariff available for every kWh exported to the (Irish) distribution network is €0.09/kWh. This situation contrasts sharply with the UK where a tariff is paid (rates dependent on supplier and tech-

nology) by the energy supplier for all kWh generated (up to 20 years) in addition to an export tariff of £0.045/kWh [5].

The adoption of EN50428 in 2007 by the Commission for Energy Regulation (CER) and subsequently the DNO Electricity Supply Board Networks (ESBN), facilitated the connection of micro-generation in Ireland. The paper reviews the technical implications of increased proliferation of such technologies in terms of distribution network impact and briefly discusses the increased proliferation of wind turbines on the distribution network in Ireland. What has occurred since 2007 is a very slow up-take on the connection of micro-generation. When one looks at the UK, to date, over 44,460 micro-generation units have been installed of which 42,590 are Photovoltaic (PV) installations [6], whereas in Ireland, metered micro-generation installations number approximately 620 of which 114 are PV with the majority of the remainder being micro-wind [7].

The major technical aspects of micro-generation are examined with a view to determining if there are any particular issues in Ireland which are hindering the development of micro-generation. The paper examines the grid-tie inverter as the significant component in micro-generation and particularly investigates the efficiencies associated with inverter operation. In particular, inverter efficiencies associated with respect to PV, as the growth technology internationally [6], and the effects of Irish insolation levels, which differ from the central European norm.

II. EN50438

What is the significance of EN50438 in respect of micro-generation? This European standard defines how micro-generation ought to be connected to the distribution network throughout the EU. There are some national deviations in respect of some settings but basically it is a common standard allowing the safe interfacing of micro-generation to the grid utilising grid-tie inverter technology. The standard therefore facilitates the standardisation of micro-generation interface unit settings among differing manufacturers supplying an EU wide market.

EN50438 divides micro-generation between single and three phase connection situations. Three phase connections are confined to a maximum of 11kWe and single phase to 16A; however, in Ireland, Finland and Cyprus the single phase maximum under EN50438 is 25A (5.75kWe).

The standard particularly suits the connection of micro-generators in residential settings in Ireland and Europe where most if not all residences only have a single phase connection.

The standard also allows the implementation of a *Supply and Fit Principle*; this principle allows the DNO to connect micro-generation without onerous checking due to the compliance of the micro-generator with EN50438. This gives the DNO a measure of confidence in exercising minimum involvement regarding supervision of the installation and commissioning of micro-generation.

III. MICRO-GENERATION & TECHNICAL CONSIDERATIONS

The majority of research confirms that it is desirable to have micro-generation connected to the distribution network; the principal concerns relate to voltage rise and unbalance on the network. These concerns resulted in the Irish DNO imposing a limit on the amount of micro-generation connected to any one sub-station or distribution transformer depending on the situation; this limit formed part of the technical submissions of the DNO to CER in 2006 [8]. The limit is 40% of the capacity of the sub-station or distribution transformer.

In practice, this limit does not seem to have hindered the development of micro-generation to-date and the DNO have indicated previously that they may review the limit in for individual particular circumstances after due consideration and analysis [9]. Three previous Irish studies indicated that in general there should be no major issues with accommodating 100% penetration levels on the distribution network [10-12]. Richardson and Keane found voltage levels could breach network constraints only under extreme conditions of minimum load and maximum generation (n-1 contingency) [11]. However, the results of the two other studies, PB Power [10] and Sunderland and Conlon [12], clearly indicate that there could be voltage rise but this rise was not detrimental to the modeled network. For example, Fig. 1 illustrates the voltage profile results as acquired by Sunderland and Conlon [12], associated with a representative Irish distribution network for varying (balanced) load and generation. Looking closer at Fig. 1:

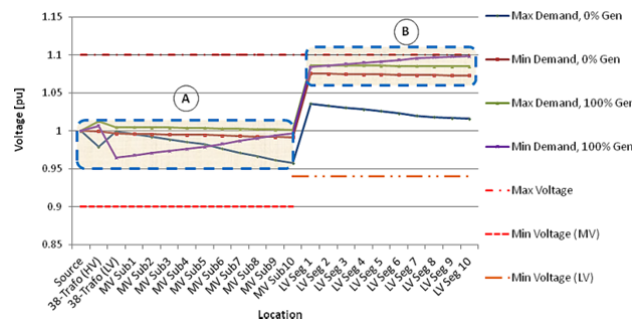


Fig. 1 System Voltage Profile [12]

At A: The network was comprised of two 38/10.5kV transformers supplying five 10kV feeders, each with ten 400kVA substations serving 312 consumers over four 400V lines per substation. The figure illustrates the voltage profile of one of the 10kV lines including a detailed consideration of one of the 400V lines. Clearly visible is the reaction of the system to varying load and generation configurations on the 10kV line

and the 38/10.5kV transformer tapping, where excessive/insufficient voltage proliferation is evident. The associated Automatic Voltage Control (AVC) has a bandwidth of 2.5%.

At B: Fig 1 illustrates the reaction of the system to varying load - generation configuration. Here, the Low Voltage (LV) consumer connections are observed. It is worthy of note that for both studies, the only scenario where the potential for voltage rise (in excess of tolerances) was with respect to maximum generation and minimum load – but for both, the tolerance was just about adhered to.

IV. TARIFF CONSIDERATIONS

As mentioned in the introduction, the FIT in Ireland has been reduced from €0.19/kWh to €0.09/kWh since April 2012 which is a major disincentive to installation; in addition no government grants of any kind are available to a householder for installation. The figures for micro-generation connections have been rising steadily from zero in 2007 to 400 in 2009 [13] and stood at over 600 as of December 2011 [7] but this figure is miniscule when compared to the UK's figure as previously indicated [6].

Whilst sound technical, economic and environmental reasons exist for encouraging distributed generation these reasons are conversely outweighed by not having a governmental grant policy with a favourable FIT which actively encourages installation. This lack of a favourable micro-generation policy, if maintained can only have a negative impact on any appreciable uptake in micro-generation installation in Ireland for the foreseeable future. Consequently, any real or perceived negative technical considerations will be moot as the 40% capacity limit will not be reached for some time. One can say that whilst the situation in Ireland is not currently stagnant it is certainly on a very slow upward trend.

V. MICRO-GENERATION MIX

The micro-generation mix as of December 2011 was predominantly micro-wind as can be evidenced from Fig. 2 [7]. Approximately 3MW of micro-generation is grid connected; this represents an increase in capacity of 25 % as compared to 2010. It is evident though that there is long way to go before the sector can make an impact on renewable energy targets.

Micro-generation Mix by Capacity

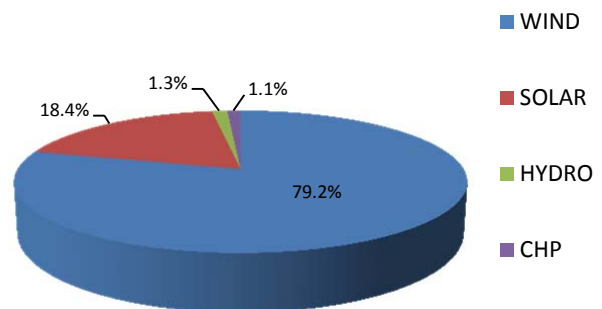


Fig. 2 Types of Installed Micro-generation in Ireland (Dec 2011) [7]

It is envisaged the proliferation of micro-wind will continue in Ireland as the predominant form of micro-generation into the future. The size of micro-wind turbines is generally in the 2-3kW region but installed capacities range from 500W up to 17kW; see Fig 3 for a breakdown of the micro-wind ratings [7]. However, under EN50438 and ESBN criteria, only technologies with ratings up to 5.75kW are considered micro-generation.

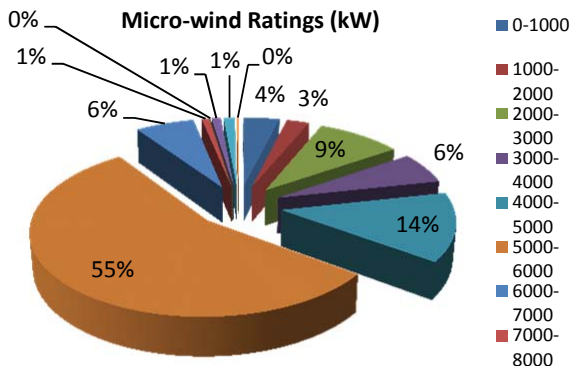


Fig. 3 Wind Turbines (small/micro) on Distribution Network [7]

It can be surmised that the majority of Irish micro-wind sites do not currently occur in urban areas due to restrictions in the planning code in respect of such installations and difficulties in the wind resource. It is therefore a technology, the majority of which is rural based. Wind is a technology that could be exporting at night during periods of low demand and is highly weather dependent. Due to its association with rural situations there could be voltage rise issues for rural networks, in the situation outlined, which may give rise to concerns. That said however, if the UK position is repeated (which itself has echoed the German priority in recent years), PV is likely to become a bigger player in Ireland in the future. Relatively speaking, PV installations experienced bigger growth compared to micro wind generation in the Irish market from 2010 to 2011 (42% compared to 20%) [7].

VI. METHODOLOGY

The methodology of this paper looks at the general issues surrounding micro-generation in Ireland but particularly focuses on the efficiency of an inverter installed in a PV installation located in city centre Dublin. One of the ways in which to compare inverter efficiency is to use the *European Weighted Average Efficiency* (EWAE). This is a common way in which to compare inverter efficiencies and the paper intends to examine the quoted EWAE of a particular inverter (SB 1100LV) against a power in versus power out simple model (average efficiency).

The average efficiency was calculated over three minute intervals and these figures in turn were averaged to provide a daily average for comparison against the quoted manufacturers EWAE. In addition, a EWAE was also calculated from the data for comparison against the manufacturers quoted EWAE. The inverter was connected to a PV array located at Dublin Institute of Technology where data was collected over a three

day period from the AM of 7th May 2010 to the AM 10th May 2010. The data was collected by means of a data logger (Sunny Boy Control Plus) with suitably modified input channels to enable the DC input voltage and current to be accurately read (50V/50A maximum). The results of the data collection were then collated, processed and plotted using Microsoft EXCELTM.

VII. INVERTER

The principal purpose of the inverter is to convert the DC input from a micro-generator to AC and then safely supply the generated power in synchronism with the connected network. The inverter is an important component in the overall conversion of the generated electrical energy and its operation and efficiency are of paramount importance regarding the micro-generator.

A. Efficiency

Utilising the data collected, efficiency was calculated on the basis of three formulae (1) conversion efficiency (2) EWAE; the EWAE is discussed in more detail later (3) 72 hour kWh efficiency

$$\eta_{conversion} = \frac{P_{AC}}{P_{DC}} \times 100\% \quad (1)$$

$$\eta_{euro} = 0.03 \times \eta_{5\%} + 0.06 \times \eta_{10\%} + 0.13 \times \eta_{20\%} + 0.10 \times \eta_{30\%} + 0.48 \times \eta_{50\%} + 0.20 \times \eta_{100\%} \quad (2)$$

$$\eta_{72 \text{ Hr kWh}} = \frac{P_{AC \text{ kWh}}}{P_{DC \text{ kWh}}} \times 100\% \quad (3)$$

The data began to be collected on 08:21 on 7th May 2010 in the manner previously outlined. In addition, the cumulative power data for the three 24hr periods was also separated into bins according to the partial loadings found in the EWAE formulae. In calculating partial efficiencies, periods when the inverter was not exporting (8W or less) were ignored; the reason for this was to examine the EWAE from an export only perspective. The EWAE was then calculated for the whole period of the data collection as per formulae (2).

B. EWAE

This was first proposed in 1991 by Prof. Heinrich Häberlin from Bern University of Applied Sciences. It is calculated by referencing several efficiencies at different operating points and weighting them according to the frequency with which they occur at a specific location in Europe. The formula reflects the fact that insolation values vary with time of day and season. Differing insolation levels give rise to differing efficiencies at part load inverter power. The first term of the EWAE formulae indicates that for 3% of the time a PV system will operate at 5% of nominal capacity; the same logic applies to the other terms. The level of DC input voltage is a significant factor also in the calculation of the EWAE but most manufacturers do not disclose it in their data sheets [14]. The difficulty then is that the EWAE is site specific and based on the frequency of specific insolation levels experienced at that site, therefore direct comparisons of inverters using EWAE is problematic. It is difficult for an inverter to be highly

efficient at all loads; the EWAE allows manufactures to optimise their inverters for mid-range loads and therefore one can compare inverters against each other using this method. The difficulty of course is that Irish insolation levels are generally less than those of mid Europe. A report by Mondol and Smyth examined efficiencies from detailed monitoring of a PV array located in Northern Ireland at the ECOS centre. This study found that the efficiency of the inverter dropped significantly when operated at less than 20% of rated capacity [15]

C. Maximum Power Point Tracking (MPPT)

The efficiency of the inverter is dependent on a number of factors, MPPT being an important one. The MPPT algorithm performs a number of functions the primary one being to match the DC input with the AC load in such a way to extract the maximum power from the input. The MPPT consists of hardware and software to enable it to perform its functions; other parameters which the algorithm needs to deal with are dynamic grid impedance and load power factor. It is the author's experience that manufacturers do not disclose any revealing details of their MPPT algorithms presumably due to commercial sensitivities. In a study by Jayanta Deb Mondol, Yohanis, and Norton it was found that inverter efficiency decreases during low partial load as the inverter consumes power for MPPT searching, grid monitoring and auto-test procedures [16].

VIII. ANALYSIS

Inverter data covering one day (7/5/10 to 8/5/10) was examined and data plots using EXCEL™ were implemented in respect of some of the parameters detailed infra.

- a) Inverter Power and Efficiency
- b) Insolation Values – Inverter and System Efficiency
- c) Energy Export
- d) Conversion Efficiency
- e) EWAE

These data plots are displayed following (Fig.'s 4 to 6) and commentary is offered in respect of the salient points of each figure in turn. Efficiency calculations were carried out encompassing all of the data for the three days; these calculations were then compared to the quoted manufacturers EWAE and are displayed in tabular format.

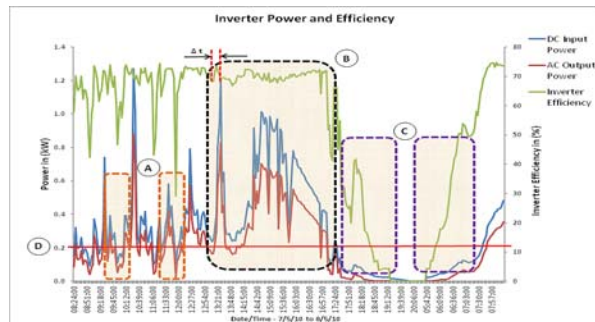


Fig. 4 SB1100LV Inverter Power and Efficiency

At A: The affect of AC/DC Power falling below the 20% threshold is illustrated.

It is apparent that drops in power below the threshold, even for relatively short periods of time have a cumulatively adverse affect on the efficiency over the long term.

At B: The plot indicates the nonlinear time relationship that is prevalent on a number of levels. Firstly, the traces relating to AC/DC power are not in phase with the inverter efficiency. Paradoxically, however, when the fall-off of the AC/DC power is further investigated (between 14:42:00 and 16:48:00), it is apparent that the inverter also supplements operational parameters by maintaining (with a degree of success) efficiency at optimal level, even with fall off in insolation (compare with Fig. 5).

At C: There is a difference in the rate of action when efficiency performance and AC/DC power is compared. It is thought that these differences are proportional to an in-built hysteresis so that the inverter doesn't react too quickly or too suddenly to drops in power or insolation which could render the system too stochastic in how energy is supplied.

At D: The lowest level of AC/DC power for which the inverter can operate at its optimal level(s)

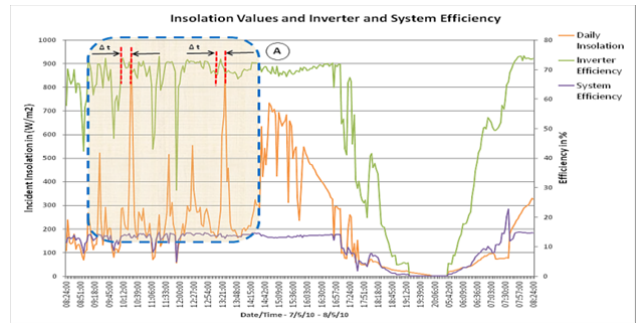


Fig. 5 Insolation Values - Inverter and System Efficiency

At A: Fig 5 indicates the nonlinear time relationship that is prevalent on a number of levels; this is consistent with Fig. 4 previous. Fig 5 also indicates that the insolation is responsible for deriving the useful power. The data plots for AC/DC power are not in phase with the inverter efficiency, similarly, the insolation plot is also phase displaced (in line with the power traces of Fig. 4).

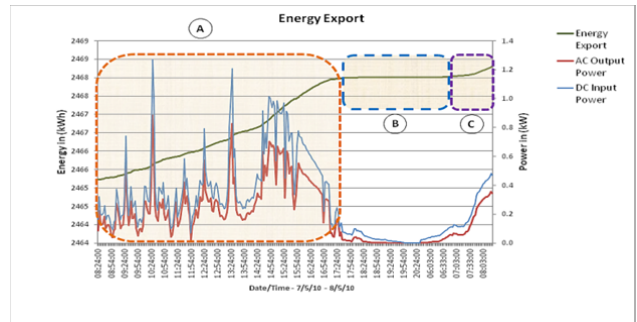


Fig. 6 Inverter Energy Export

In terms of energy production, three regions of operation are illustrated in Fig. 6 above

At A: Energy accumulation; here insolation levels are sufficient for the PV array to produce energy which accumulates over the period identified

At B: Static operation; here insolation levels are insufficient to derive useful energy.

As insolation levels dropped the energy export remained more or less static from 18:24 onwards until the time the inverter switched off at 20:03.

At C: The inverter switched on again at 05:24 but did not begin to export until 06:12 according to the data. Power developed during this period seems to have been consumed by the inverter feeding its operational losses as can be evidenced by the flat line of the energy export graph. There is then a gradual export evidenced from the graph after this non-exporting but generating period.

These periods seem to occur at low insolation levels < 300 W per m² which coincide with the self-consumption of the low energy produced. The average daily efficiency over the three 24 hr periods was calculated using the three minute efficiencies, these figures are displayed in Table 1 below.

TABLE I
INVERTER DAILY OPERATING EFFICIENCIES V QUOTED EWAE

Date	24Hr Average Efficiencies (%)	Manufacturers Quoted EWAE (%)
7/5/10 - 8/5/10	62.75	90.4 *
8/5/10 - 9/5/10	64.46	90.4 *
9/5/10 - 10/5/10	59.21	90.4 *

* EWAE efficiency is also quoted as 91.6% in manufacturer's data sheet

The 72 hr average, 72 hr EWAE and 72 hr kWhr efficiencies were also calculated from the data. These figures are displayed in Table 2

TABLE II
INVERTER 72 HR EFFICIENCY

Date	72Hr Average Efficiency (%)	72Hr EWAE Efficiency (%)	72 Hr kWhr Efficiency (%) (7/5/10)
7/5/10 - 10/5/10	60.85	68	67.11

There is approximately a 7% discrepancy between the 72 hr average efficiency and the calculated EWAE; part of the reason for this may arise from the fact that not all AC power data was included when calculating the EWAE figure (when inverter was not exporting), though this may not explain the discrepancy fully. The 72 hour kWh efficiency was quite close to the calculated EWAE (within 1%). All generated DC kWhrs and exported AC kWhrs was included for this calculation. A data plot of per unit kW loading against efficiency over the period of 7/5/10 to 10/5/10 is shown in Fig. 7. The inverter performance at various loadings can be seen when the inverter is exporting useful energy.

The kWh efficiency figure compares reasonably well in respect of the inverter efficiency as shown in Fig.7 where the inverter shows efficiency hovering around the 70% mark when the partial efficiency goes above 0.2pu kW loading. When looking at the Tables 1 and 2 previously it can be seen that the manufacturers quoted EWAE is somewhat removed from the other calculated average efficiencies during a particular snapshot of the Irish climate and raises some questions regarding how the EWAE can be relied upon in situations where the climatic conditions differ from the EWAE conditions.

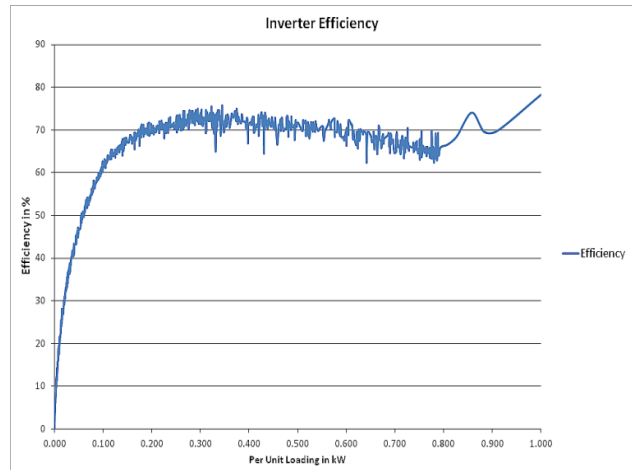


Fig. 7 Per Unit kW loading v Efficiency 7/5/10 - 10/5/10

Fig.7 clearly illustrates, optimal efficiency with respect to power delivery is in the range 0.2pu and 0.8pu. The apparent discrepancy observable from 0.8-to-1pu can be explained by the fact that for the site in question, the number of opportunities for the power to be in this range is significantly less when compared to the mid-range. This is more a testimonial of the resource at the site in question as opposed to the capability of the inverter technology itself

IX. CONCLUSIONS AND FUTURE WORK

A potential purchaser could be forgiven in respect of being misled as to the true operating efficiency of the inverter if the only benchmark used for efficiency was the quoted EWAE. One must also take account of how the actual installation site differs from the EWEA reference site in terms of insolation levels throughout the year not to mention variations in local conditions. This is critically important when assessing the economic viability of quantifying energy harvesting and the suitability and particularly the selectivity of inverter hardware. A number of general observations can be made in respect of the research and findings

- i. The inverter efficiency as plotted throughout the period 7/5/10 to 8/5/10 varies with insolation levels. As the insolation levels falls to 700 W/m² and below the inverter operating efficiency appears to fall significantly

- ii. The overall system efficiency is generally below 15% (Incident solar power compared to AC kW produced)
- iii. The average efficiency from 7/5/10 to 8/5/10 is 62.75% (EXCEL™ Data)
- iv. The calculated EWAE from 7/5/10 to 10/5/10 is 67.99% (EXCEL™ Data)
- v. It can be concluded at the very least that the inverter did not perform at the stated EWAE for all its working range, particularly at partial loadings
- vi. There are periods of time when the inverter is actually receiving a DC input but does not convert this to AC
- vii. There are periods when the inverter has an AC output available but does not export to the grid. It stops exporting when its efficiency falls below approximately 18% (EXCEL™ Data)
- viii. The data supports the contentions of Jayanta Deb Mondol, Yohanis, and Norton that inverter efficiency decreases during periods of low partial loads
- ix. The contentions of Mondol and Smyth relating to efficiency of the inverter dropping when operating at less than 20% of rated capacity are likewise supported by the data
- x. In general, the AC output follows the DC input pattern

In terms of future work it would be interesting to further refine the above results to validate the findings by gathering finer resolution data in terms of one minute or less and having a larger data set covering four seasons. Additionally, it would also be interesting to develop a formula similar to the EWAE but adjusted to Irish climatic conditions; perhaps developing differing weightings and or multipliers to the existing formulae or an adjustment factor. Likewise, there appears to be no way currently in which to optimise an inverter's algorithm to dynamic climatic conditions which would perhaps offer a method whereby increased efficiency could be derived using a feedback mechanism from actual insolation received on site.

It is noteworthy that micro-generation offers more benefits than not but the current micro-generation policy (lack of installation grant and incentivized FIT tariff) acts as a major disincentive to future development. It would be worthwhile to construct an argument for submittal to government on the basis that the current policy is counterproductive not just in the short term but could have long lasting consequences for Ireland in catching up on its EU partners in relation to micro-generation. In short, any impetus that now exists could be lost and would require more effort to start up again rather than encouraging the current situation to develop impetus incrementally.

REFERENCES

[1] EU, "Directive of the European Parliament and European Council (2009/28/EC) on the Promotion of the Use of Energy from Renewable Sources," ed, 2009.

[2] SEAI, "Renewable Energy in Ireland 2011 (8th August)," Sustainable Energy Authority of Ireland, Dublin 2011.

[3] DCENR, "Strategy for Renewable Energy 2012 - 2020, Department of Communication, Energy and Natural Resources," ed, 2012.

[4] DCENR, "People Power - Minister Ryan Announces Incentives for Micro Generation," ed. Dublin: Sustainable Energy Authority of Ireland, 2009.

[5] DECC, "Feed-in Tariffs: Get Money for Generating your own Electricity," DECC, Ed., ed: Department of Energy and Climate Change 2013.

[6] AEA. (2011, 25/4/13). Tracking the Progress of Microgeneration in the UK. The AEA Microgeneration Index (4). Available: <http://energyresearchgroup.files.wordpress.com/2011/09/aea-microgeneration-index-issue-4.pdf>

[7] Sunderland K, "Total Installed Capacity of Micro Generation (Ireland, 31st December) ", Murphy L, Ed., ed. Dublin: ESBN, 2011.

[8] CER. (2006, 13/3/10). Responses to CER Consultation Paper on Micro-generation. Available: <http://www.cer.ie/en/electricity-distribution-network-current-consultations.aspx?article=5b5a122e-5182-42a2-852c-00e71bc7c949>

[9] B. O'Connor, "Discussion - EN50438," ed. Dundalk: ESBN, 2010.

[10] PB Power, "Cost and Benefits of Embedded Generation in Ireland," SEAI, Dublin 2004.

[11] P. Richardson and A. Keane, "Impact of High penetrations of Micro-generation on Low Voltage Distribution Networks," presented at the CIRED 20th International Conference on Electricity Distribution, Prague, 2009.

[12] K. Sunderland and M. F. Conlon, "The Role of Micro Wind Generation in Ireland's Energy Future," presented at the Universities Power Engineering Conference, Padova, 2008.

[13] T. Hearne, "Current Status of Micro-generation in Ireland," presented at the DIT Microgeneration Workshop Nov 09, Dublin, 2009.

[14] F. P. Baumgartner, et al., "Status and Relevance of the DC Voltage Dependency of the Inverter Efficiency," in 22nd European Photovoltaic Solar Energy Conference and Exhibition, 3-7 September 2007, Fiera Milano, 2007.

[15] J. D. Mondol and M. Smyth, "Monitoring of Roof Mounted Photovoltaics at ECOS Millennium Environmental Centre," University of Ulster, Belfast 2004.

[16] J. D. Mondol, et al., "Optimising the Economic Viability of Grid-connected Photovoltaic Systems," Applied Energy, vol. 86, pp. 985-999, 2009/8// 2009.