SDAR* Journal of Sustainable Design & Applied Research

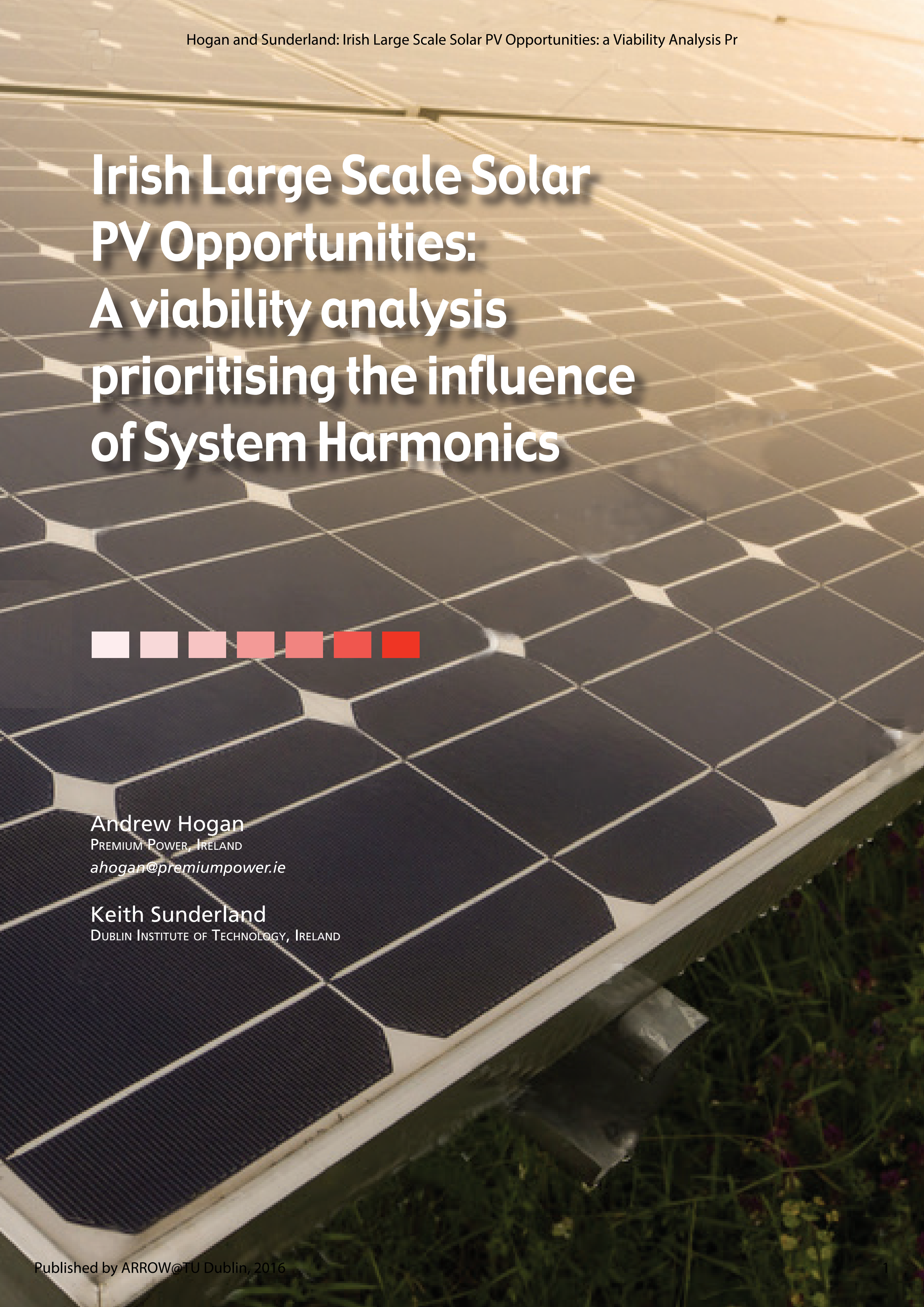
Volume 4 | Issue 1 Article 4

2016-11-16

Irish Large Scale Solar PV Opportunities: a Viability Analysis Prioritising the Influence of System Harmonics

Andrew Hogan
Premium Power Ireland, ahogan@premiumpower.ie

Keith Sunderland
Technological University Dublin, keith.sunderland@tudublin.ie



Irish Large Scale Solar PV Opportunities: A viability analysis prioritising the influence of System Harmonics

Andrew Hogan
Premium Power, Ireland
ahogan@premiumpower.ie

Keith Sunderland
Dublin Institute of Technology, Ireland

Abstract

This paper considers the techno-logistical considerations involved in designing for a large scale (>100 kW) distributed generation (DG) opportunity. The logistical considerations involve site feasibility assessment in terms of resource, land requirements and PV plant design, whereas the technical considerations prioritise the impact that PV inverters can have on the performance of a power system; particularly in the context of the detrimental effects manifested by harmonic distortions. The analysis demonstrates that without proper consideration of the PV system configuration and how PV inverters are employed, capacity rating breaches will affect both the DSO and the consumer. Ultimately, the results point towards a need for policy measures that encourage power system studies at the logistical stage of development to encourage what is 'the ultimate' in a sustainable energy resource.

Keywords:

Solar photovoltaic (PV), feasibility study, PV system design, grid codes, harmonic distortion.

Glossary

AC	Alternating Current	*PCC*	Point of Common Coupling
DG	Distributed Generation	*PQ*	Power Quality
DSO	Distribution System operator	*RES-E*	Renewable Energy Supply-Electricity
EPIA	European Photovoltaic Industry Association	*RES-H*	Renewable Energy Supply-Heat
IWEA	Irish Wind Energy Association	*RES-T*	Renewable Energy Supply-Transport
LV	Low Voltage	*SNSP*	Synchronous Non-Synchronous Penetration
MV	Medium Voltage	*TSO*	Transmission System Operator
PV	Photo-Voltaic	*VTHD*	Voltage Total Harmonic Distortion
PFC	Power Factor Correction	*PCC*	Point of Common Coupling
NREAP	National Renewable Energy Action Plan		

1. Introduction

IIn the context of a sustainable energy future for Ireland, the Irish Government has implemented policy aimed at reducing carbon emissions, reliance on fossil fuels and providing the means to accelerate growth within the renewable energy sector. These policies promote a sustainable renewable energy sector in Ireland. The Government's National Renewable Energy Action Plan (NREAP) for instance, sets a mandatory target of 16 % for renewable energy in three key areas — electricity, heat and transport. The designated contributions towards each area include 40% for electricity (RES-E), 12% for heat (RES-H) and 10% for transport (RES-T). Such policies, however, have the potential to introduce major technical problems for the transmission/distribution system operators (TSO/DSO) in terms of availability, power system stability and power quality (PQ). These technical problems are already prevalent and have led to a cap of 50% on synchronous non-synchronous penetration (SNSP) on national grids (Eirgrid, 2009).

In Ireland a large emphasis has been placed on wind. Wind, particularly large-scale wind, is generally perceived as the primary renewable energy technology that will help Ireland meet its 2020 target of 40% of all electricity to come from renewable sources. In 2016, the Irish Wind Energy Association quoted 2,441 MW of installed wind capacity in the Republic of Ireland (IWEA, 2016). This is substantial when compared to the country's actual electricity demand of 5000 MW. These figures would suggest that Ireland is not too far away from achieving the 40% RES-E target. However, antagonistic factors including wind resource intermittency and negative public perception of large wind plant, as well as the environmental challenges such deployments face, suggest that wind alone may not be enough to meet the 40% RES-E target.

Solar PV, which is often overlooked and underestimated in Ireland, is a renewable technology that could be used to complement wind power and add to the current renewable power mix in Ireland. The notion that Ireland does not possess a solar resource capable of supporting a sustainable PV sector has been proven incorrect in recent times. The European Photovoltaic Industry Association's (EPIA) global outlook for PV in 2014 showed how Ireland's solar resource is equivalent to that in the UK and parts of mainland Europe (EPIA, 2014). Solar Power Europe reported that by the end of 2015 the UK had an installed PV capacity of 9.2GW (SPE, 2015), which is extraordinary when compared to Ireland's estimated 3MW (TEA, 2014). According to the Irish Solar Energy Association however, Ireland's solar insolation levels are 78% of the level received in Madrid and are equal to the levels experienced across sites in the UK (ISEA, 2014)

The statistics presented in the previous paragraph suggest that the solar resource should not be considered as the exclusive barrier to PV deployment in Ireland. One can therefore extrapolate that the challenges facing the PV sector are actually more related to development opportunities and the considerations therein.

This paper will outline a structured approach to developing a PV system in Ireland. Starting with the high level design of a 1 MW PV facility, the paper will describe the key steps involved in a PV

https://arrow.tudublin.ie/sdar/vol4/iss1/4
DOI: https://doi.org/10.21427/D77P4S

feasibility study before carrying out harmonic analysis on the proposed 1MW PV system installation. In this regard, the advanced power systems modelling tool (DIgSILENT) is employed to assess a 1MW PV facility that is connected to the distribution network at medium voltage (MV) i.e. 10kV – 38kV. The results of the harmonic emissions investigation are subsequently used to determine if a harmonic filtration unit is required. Harmonic filters can be designed to limit the impact harmonic distortion levels can have on electrical power systems.

2. Background

Resource estimates prove that largescale solar PV can be a viable alternative source of energy (ISEA, 2014). Such a resource could be used to complement the large volumes of installed wind capacity in Ireland. However, evidence of the resource alone will not be enough to achieve a sustainable PV sector in Ireland.

Feasibility studies that not only look at resource but focus on strategies that help improve conversion efficiencies, from energy production to final consumption, are essential to accomplish a successful/attractive PV sector. Selecting a site close to where the load is consumed immediately improves system performance and contributes positively to the overall power demand of the network. Research identifies transmission and distribution network losses as the single largest use of electrical energy in any power systems (Targosz, 2008).

There are also underlying factors that are often neglected, but are crucial to sustained PV development and growth. The DSO in Ireland, through industry standards such as EN50160, must ensure that *Voltage Total Harmonic Distortion* levels *(VTHD)* do not exceed 8% for 95% of the time. Through the Irish distribution codes, the DNO has designated an upper limit of 2% *VTHD* on harmonic emissions for all connected generators. The attention focused on non-linear PV inverters in this paper, prompted by research carried out by Benhabib (2007), relates to the technical issues that can arise where multiple sources of harmonic distortion are connected to any given power system.

Harmonics, relating to solar PV, and as a power quality (PQ) concern for power network operators, are of particular interest for two reasons. Firstly, solar PV systems, by virtue of how they generate electricity, utilise non-linear high-frequency switching devices (inverters) to produce AC power, which is required for synchronisation with electricity grids.

Secondly, Benhabib's (2007) research, which involved 96 residential homes where small grid-tied PV systems were connected to the DSO's 400V network, demonstrated how connecting an accumulative non-linear load (inverter) in parallel to a common electrical bus systematically caused the harmonic distortion levels to rise. The final scenario associated with Benhabib's work assessed 96 grid-tied inverters coupled with four non-linear loads and the associated analysis concluded that the *VTHD* levels could reach 51% (Benhabib, 2007).

High levels of *VTHD* on the Irish distribution network will lead to PV system curtailments. Such action is unavoidable if compliance with the EN50160 standard cannot be achieved, which will ultimately lead to the failure of critical network components. These failures include the overheating of transformers, overloading of neutral conductors, nuisance tripping of circuit breakers, over-stressing of PFC (power factor correction) capacitors, overheating of windings in induction motors and likely damage to converters, telecommunications and other electronic equipment.

3. Site feasibility study

Large-scale renewable energy projects require careful consideration of critical criteria in order to achieve optimum performance. Such criteria includes resource, land requirements, customised system design and proximity to distribution load centres, each one interlinked and interdependent.

The methodology involved in allocating a site to install the PV generator is illustrated in Figure 1. A consideration of the site requirements as they apply to a 1MW PV facility is considered in the following sections. This includes a system configuration (Section 3.1) and land availability (Section 3.2) perspective, with Sections 3.3 and 3.4 providing a resource and demand consideration respectively.

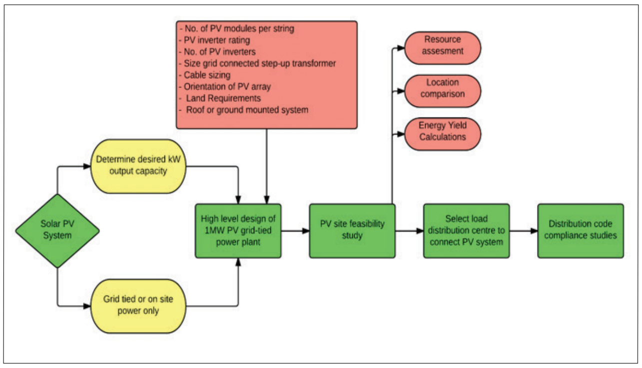


Figure 1: Feasibility study and PV system design process chart

3.1 PV System Design

The number of Mitsubishi MLE-260 PV modules per string, and subsequently the number of PV strings within an array, is governed by the PV inverters DC electrical input characteristics. The selected PV inverter, which is an SMA Sunny T60, is manufactured to EN 50438 and tested to harmonic emissions standard EN 61000-3-12.

The voltage, within a series-connected string, increases by 30.9V as each Mitsubishi 260 W PV module is added. In this situation the current remains constant at 8.59A. To achieve maximum power at the PV inverters input terminals, additional strings are connected in parallel. Connecting similar-sized PV strings in parallel increases the derived current by 8.59A with every string added in parallel. In this regard, adding panels in parallel has no effect on the system voltage. So, for 1kV (constant) at maximum power:

- No. of inverters: total system capacity / inverter max AC power output rating,
  (1000kW/60 kW) = 17 inverters
- No. of modules per string:
  (maximum inverter input voltage/PV module output voltage),
  1000 V/30.9V = 32 PV panels/string

- No. of strings/array:
  (maximum inverter input current/PV module output current), 110 A / 8.59 A = 13 strings/array

A summary of the system configuration is provided in Figure 2.

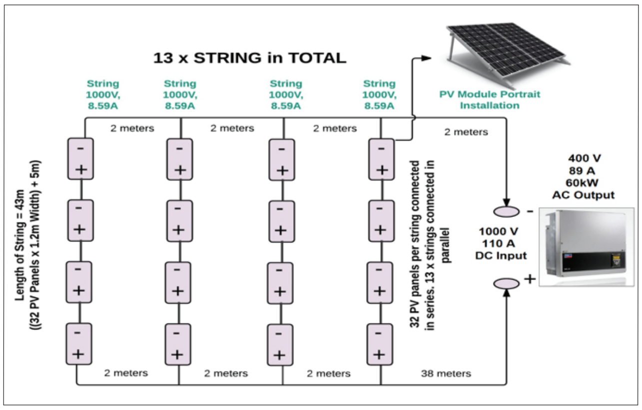


Figure 2: Configuration of 1MW PV array.

3.2 Land Requirements

Previous research carried out by SRA (2012) demonstrates how ground-mounted PV systems are land intensive with respect to the power they produce (SRA, 2012). The total land requirement for the 1MW facility has been estimated using the dimensions listed in Figure 2 as follows:

- Total area of PV array:
  (length of string) x (width of 13 strings + associated row spacing), 43 m x (13 x 2) = 1,118 m²
- Total Land Requirement:
  (area of 1 array) x (total no. of arrays)
  1,118 m² x 17 = 19,006m² or 4.7 acres

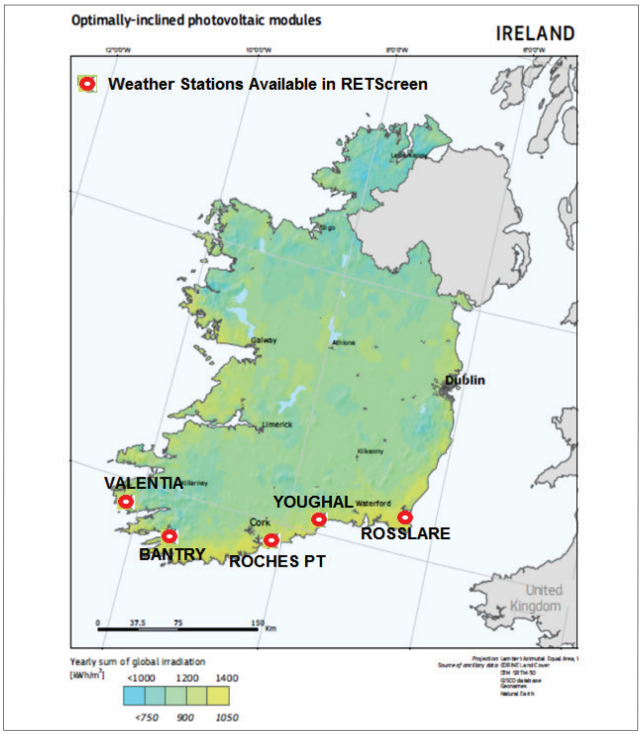


Figure 3: Solar radiation map.

The land requirements calculated above are consistent with industry guidelines. Miller (2012), who is supported by Brooks (2013), explains how the PV array area for a well-designed 1MW facility can vary between 10,000 m² (2.5 acres) to 20,000 m² (five acres) (Miller, 2012). The variance in land area is dependent on solar resource and V-module efficiencies.

3.3 Resource and Energy Yield Analysis

Solar irradiance maps, as illustrated in Figure 3, are employable to identify locations in Ireland with a suitable solar resource for large-scale power generation. In the analysis presented here, southern Ireland is prioritised, with consideration specifically applied to Valentia, Bantry, Roches Point, Youghal and Rosslare.

Once a range of locations with appropriate irradiance levels is identified, historical daily resource levels are obtainable through proprietary software such as *RETScreen* (NRC, 2015). Monthly energy yield estimates are subsequently determined for each location as illustrated in Figure 4, which compares the potential energy yield at each location considered.

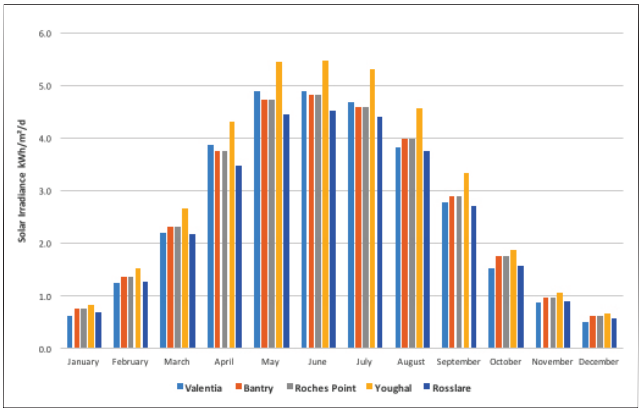


Figure 4: Monthly energy yield comparative analysis.

3.4 Load Distribution Centre

To maximise the potential yield of a PV system, system losses should be minimised by ensuring the solar power is consumed as close as possible to where it is produced. Therefore, reducing the effects of energy distribution systems (such as cable systems) is a priority in this regard. In the context of the counties considered, Co Cork, as portrayed in Table 1, has the largest electrical load requirement.

Table 1: Electrical Energy Balance for Southern Regions (AIRO, 2014)

2014 Electricity Usage	National ktoe	National GWh	Cork GWh	Wexford GWh	Kerry GWh
Industry, Commercial & Public Services Electricity	1434	16674	3815	504	518
Residential Electricity	663	7709	1781	245	248
Residential & Industrial Electricity Consumption	2097	24384	5596	749	766

https://arrow.tudublin.ie/sdar/vol4/iss1/4
DOI: https://doi.org/10.21427/D77P4S

Therefore, from an installation location perspective, the priority locations are Bantry, Roche's Point or Youghal, all located in County Cork.

4. Power system modelling

The proposed 1MW PV facility has been simulated using the system design in Section 3.

The harmonic analysis methodology was conducted under the following test conditions:

- Obtain source impedance data from *ESB Networks* for two substation classifications; see scenario one (high impedance) and scenario two (low impedance) below.
- Model 17 x PV inverters in DigSILENT software using harmonic data from SMA Sunny T60 EN50438/2013 test certificates (SMA, 2015).
- 17 x 60 kW inverters are connected in stages with the aggregated voltage harmonic emission levels measured at each stage.
- Scenario analysis to assess the impact of source impedance and cable capacitance using parameters in Table 2.

Table No.2: Parameters for Harmonics Analysis

Parameter	Scenario 1	Scenario 2
PV Installed Capacity	1 MW	1 MW
LV Transformer Size	2 MW	2 MW
MV Substation Voltage	10 kV	20 kV
MV Substation Impedance	4.8 Ω	2.8 Ω
MV Cable Size	120 mm²	120 mm²
MV Cable Distance (short)	50 meters	50 meters
MV Cable Distance (actual)	2 kM	2 kM

- Record % *VTHD* values at PV system LV bus and MV substation (PCC).
- Harmonic emission levels are compared to % *VTHD* limits set out in the distribution code for generators.

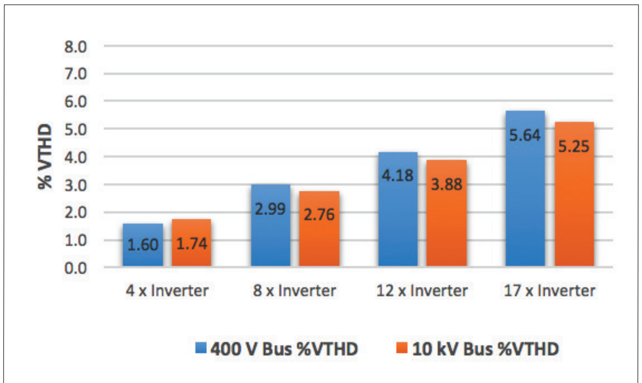


Figure 5: Voltage harmonic analysis – 50m cable run (high Z network).

4.1 Harmonic Analysis Results

The harmonic analysis results, outlined in Figure 5, illustrate clearly that the harmonic emission levels increase proportionally with the addition of PV inverters. The 17 x 60kW PV inverters generate a current that is disproportional to the utility supply, thereby distorting the network voltage.

Non-linear loads, such as PV inverters, draw a non-linear current that is disproportional to the applied voltage (ABS, 2006). Network/source impedance (Z), obtained from the local utility company, plays a vital role in determining the magnitude of voltage harmonic distortion, which is illustrated in Figures 6 and 7. This is because the voltage harmonic distortion is the manifestation of non-linear current interactions with the networks impedance.

Another significant factor, realised while modelling the MV cable, was the impact that cable capacitance has on the overall *VTHD* levels. The harmonic emission levels observed, when a 120 mm² 50 m MV cable run was simulated, were almost 20% - 40% less than those calculated with the actual cable length of 2kM (see Figure 5 and 6 and Table 3). All cables contain resistive, inductive and capacitive characteristics. The capacitive element is dominant in high and medium voltage cables. In relatively long high/medium voltage cable runs, the cable capacitance amplifies the network harmonics, which is evident in the results recorded in Figure 6 and Table 3.

The cells highlighted in red within Table 3 represent the points where the voltage harmonic distortion levels breach the distribution codes limit of 2% for grid-connected generators. Although breaches occur when a cable run of 50m is used, the results reveal how an influx

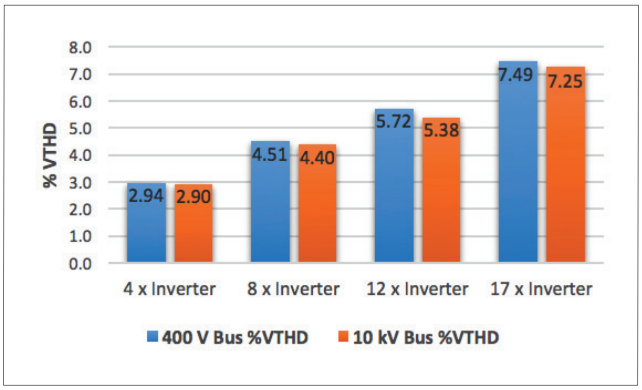


Figure 6: Voltage harmonic analysis – 2kM cable run (high Z network).

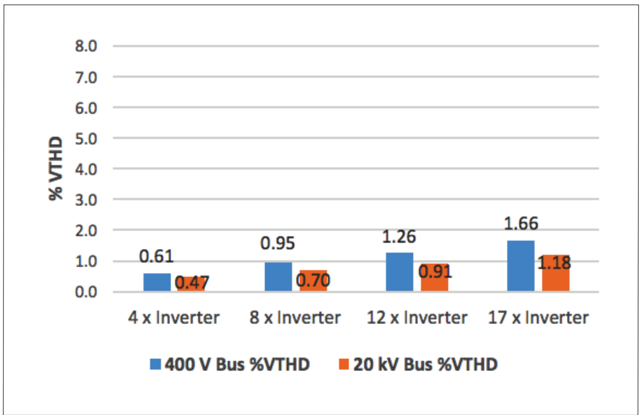


Figure 7: Voltage harmonic analysis – 2kM cable run (low Z network).

of long cable runs and non-linear equipment can exacerbate the magnitude of the distribution systems voltage distortion.

4.2 Mitigation

To mitigate against the high harmonic currents, a passive harmonic filtering solution is sized using DigSILENT software. Passive filters are L-C circuits where an inductor (L) is connected in series with a capacitor (C). The passive filtering solution, which is connected in parallel with the non-linear PV inverters, is used to absorb the current harmonics; reducing the overall *VTHD* (see comparative results in Table 4). With all PV inverters operating at 100% (full) capacity, the filters reactive power and tuning frequencies were adjusted and the VTHD levels at 10kV substation were observed. The filter set-up was continually adjusted until the VTHD levels fell below 2% at the 10kV point of common coupling (PCC).

Table 3: Harmonics Results Summary

Scenarios	Inverter kVA Output	50 M Cable/OH Line 400 V Bus %VTHD	50 M Cable/OH Line 10 kV Bus %VTHD	2 km Cable/OH Line 400 V Bus %VTHD	2 km Cable/OH Line 10 kV Bus %VTHD
0 x Inverter	0 kVA	0	0	0	0
4 x Inverter	240 kVA	1.60	1.74	2.94	2.90
8 x Inverter	480 kVA	2.99	2.76	4.51	4.40
12 x Inverter	720 kVA	4.18	3.88	5.72	5.38
17 x Inverter	1,020 kVA	5.64	5.25	7.49	7.25

Table 4: % *VTHD* results with and without passive filter

Scenarios	Inverter kVA Output	With Filter 400 V Bus %VTHD	With Filter 10 kV Bus %VTHD	Without Filter 400 V Bus %VTHD	Without Filter 10 kV Bus %VTHD
0 x Inverter	0 kVA	0	0	0	0
4 x Inverter	240 kVA	0.43	0.46	2.94	2.90
8 x Inverter	480 kVA	0.86	0.91	4.51	4.40
12 x Inverter	720 kVA	1.28	1.38	5.72	5.38
17 x Inverter	1020 kVA	1.81	1.95	7.49	7.25

The cells highlighted in red within Table 3 represent the points where the voltage harmonic distortion levels breach the distribution codes limit of 2% for grid-connected generators. Although breaches occur when a cable run of 50m is used, the results reveal how an influx of long cable runs and non-linear equipment can exacerbate the magnitude of the distribution systems voltage distortion.

5. Conclusion

This paper presents a consideration of large-scale PV systems and the viability of same with a particular focus on the considerations/ramifications of system harmonics for the distribution network operator. The results show a systematic rise in voltage harmonic distortion, at both LV and MV systems, as additional PV inverters are connected in parallel to the network. Although PV inverters introduce non-linear currents to power systems and act as a source for *VTHD*, their impact on the power systems overall *VTHD* is minimal when compared to other influential factors.

The research here also identifies the adverse effect long cable runs can have on the networks overall *VTHD* emission levels as a consequence of the associated increased capacitance. This is signified in Table 3 and Figure 6 where the voltage harmonic distortion was amplified by almost 50% when the cable run was increased from 50m to 2km. The analysis, however, identifies source impedance as having the greatest effect on the overall harmonic distortion levels. Although the PV inverters act as a harmonic source, high impedance networks significantly amplify the distortion levels. This amplification not only occurs at the point of common coupling (PCC) to the grid, but at the local switchgear where the PV inverters are connected as well.

Simulations that consider the introduction of a passive filter, which can absorb harmonic currents, show how the *VTHD* on site can be significantly reduced (Table 4). Without the utilisation of a passive filter, it is unlikely that the PV system in Scenario 1 would ever be called upon to export power to the distribution network due to the high harmonic emissions caused by the PV inverters, cable capacitance and high source impedance.Compounded with this mitigation concern, other system performance viability impacts that are created from increased harmonic distortion proliferation include component failures, prolonged outages and reduced life cycles for PV plant. Such (harmonic) proliferations will effectively make PV in Ireland unsustainable and non-profitable without appropriate corrective measures.

However, the research presented here suggests that the biggest challenge that may face PV developers in the future is not the problems caused by PV inverter induced harmonic emissions. Developers, who are granted a connection to the grid — but at a high impedance point — are inevitably at a disadvantage. They may incur higher installation costs, e.g. additional MV switchgear and filtration may be required to achieve compliance with distribution code limit of 2% *VTHD* at the PCC.

https://arrow.tudublin.ie/sdar/vol4/iss1/4
DOI: https://doi.org/10.21427/D77P4S

References

ABS. (2006). *Control of Harmonics in Electrical Power Systems.* New York: American Bureau of Shipping.

AIRO. (2014). *Census Mapping. Retrieved* Nov 1st, 2015, from http://airo.maynoothuniversity.ie/mapping-resources/airo-census-mapping/local-authority-modules

Baggini, A. (2008). *Handbook of Power Quality* (1 ed.). Bergamo: John Wiley & Sons.

Barrett, D. M. (2015). *Transmission Networks – Electricity Markets*. Dublin: DIT.

Benhabib, M. (2007). Harmonic effects caused by large scale PV installations in LV network. Barcelona: Leonardo Power Quality Group.

Brooks, W. (2013). *PV Installation Professional Resource Guide*. New York: NAPCEP.

Chapman, D. (2001). *Harmonics – Causes and Effects*. London: Copper Development Association.

DGS, G. E. (2009). *Photovoltaic Systems: A Guide for installers, architects and engineers* (2nd ed.). London: Earthscan.

Dykes, P. (2011). EU Solar Days - Solar Energy in Ireland. Wexford: SEAI.

ESBN. (2015). *Distribution Code*. Dublin: Distribution System Operator ESB Networks.

Fassbinder, S. (2014). Passive Filters. European Copper Institute.

Ging, J. (2013). Harmonic Issues and their Impact on Customer Connections. Dublin: EirGrid.

ISEA. (2014). *Submission for Green Paper on Energy Policy in Ireland*. Dublin: Irish Solar Energy Association.

IWEA. (2016). *Wind Energy Statistics*. Retrieved June 22nd, 2016, from http://www.iwea.com/windstatistics

Markvart, T. (2008). *Solar Electricity* (2ns ed.). West Sussex: John Wiley & Sons.

Miller, A. (2012). *Utility Scale Solar Power Plants: A Guide for Developers & Investors*. International Finance Corporation (IFC).

Montana, G. P. (Anon). *The Power of Solar Energy*. Retrieved November 7th, 2015, from http://www.montanagreenpower.com/solar/curriculum/lesson6.php

Rashid, M. H. (2011). *Electronics Handbook: Devices, Circuits and Applications* (3rd ed.). Elsevier.

SEAI. (2012). *Best Practice Design Guide Photvoltaics*. Dublin: Sustainable Energy Authority Ireland.

Shah, N. (2013). *Harmonics in Power Systems –- control, causes and effects*. Alpharetta, GA: Siemens.

SMA. (2016, April 22nd). Pricing for ST 60 PV Inverters.

SMA. (2015). *SUNNY TRIPOWER 60*. Retrieved 11 11, 2015, from http://www.sma.de/en/products/solarinverters/sunny-tripower-60.html

SPE. (2015). *Global Market Outlook*. Solar Power Europe.

SRA. (2012). *Solar Power Analysis and Design Specifications*. Houston: Environmental Protection Agency.

Stapleton, G. (2012). *Grid Connected Solar Electric Systems*. New York: Earthscan.

Targosz, R. (2008). *REDUCING ELECTRICITY NETWORK LOSSES*. Retrieved Nov 1st, 2015, from http://www.leonardo-energy.org/reducing-electricity-network-losses

Tipperary Energy Agency, 2014. Ireland's Largest Photovoltaic Solar Panel Project is completed. Available at: http://tea.ie/irelands-largest-photovoltaic-solar-panel-project-is-completed/

Varatharajan, A. (2014). Harmonic Emission of Large PV Installations. Dresden, Germany: Renewable Energy and Power Quality Journal.

WDC. (2010). *Regional Enegy Balance & Biomass Heating Demand Estimates for 2020*. Galway: Northen Periphery Program.

WEC, W. E. (2007). *Survey of Energy Resources*. World Energy Council.