The Effect of Distribution Network on the Annual Energy Yield and Economic Performance of Residential PV Systems under High Penetration

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Abstract

Technological advances, environmental awareness and, in several countries (including the UK), financial incentives lead to the adoption of PV (photovoltaic) systems. Economic viability, an important consideration for investment in residential PV, is dependent on the annual energy yield which is affected by distribution network based factors such as point of connection to network, network hosting capacity, load profiles etc. in addition to the climate of the location. A computational algorithm easy on resources is developed in this work to evaluate the effects of distribution network on the annual energy yield of residential PV systems under scenarios of increasing PV penetration. A case study was conducted for residential PV systems in Newcastle upon Tyne with a generic UK distribution network model. Results identified penetration levels at which PV generation curtailment would occur as a consequence of network voltage rise beyond grid limits and the variation in the percentage of annual energy yield curtailed among the systems connected to the network. The volatility of economic performance of the systems depending on its location within the network is also analysed. The study also looked at the impact of the resolution of PV generation profiles on energy yield estimates and consequently economic performance.

Keywords

PV systems; curtailment; generation profile; energy yield; grid-connected; load profile

1. Introduction

Governments across the world are ambitiously focussing on solar energy exploitation. This is mainly due to climate change, CO_2 emission reduction targets and consequent renewable energy obligations such as the European 20/20/20 targets. To drive installation of PV systems, governments provide financial incentives to PV system owners as the adoption of the technology still requires some market support. In the UK, the government Feed-in-Tariff (FIT) has supported the development of grid-connected distributed (micro) PV generation, with the majority of such installations being residential [1]. For every unit of electricity generated by a PV system the FIT scheme provides the system owners a price which is between 1 and 2 times the per unit price of electricity. In the case of a residential owner installing a PV system, the system meets all or part of their energy demand and exports any surplus energy available to the grid subject to the customer's contractual agreement with the distribution system operator. For residential PV system owners, the economic performance of the system with respect to their electricity costs is an important factor which influences the adoption of PV systems.

1.1 Significance of annual energy yield estimates in economic analysis of PV systems

Levelised cost of energy (LCOE) is a common parameter used for financial comparison of renewable energy systems and evaluation of their economic viability. It is defined as the ratio of annualised life time revenue (less costs) from PV generation to the annualised life time energy yield from the PV system [2, 3]. The annual revenue from the system is dependent on the energy generated. Net present value (NPV) is another parameter commonly used to assess the long-term viability of renewable energy systems [3]. It is defined as the net discounted cash flow over the system lifetime. It is numerically the same as the numerator of LCOE. Both LCOE and NPV consider the financial returns over the system lifetime i.e. the long term benefits. They look at PV generation alone without consideration of demand. As such these parameters are particularly useful for large commercial systems, such as solar farms, where profitability is expected in the long-term (PV system ownership is similar to that of a conventional generating plant) and local demand profile is not relevant.

Prosumer (***Pro***ducer and con***sumer***) is a term that can be used to describe a residential consumer installing a grid-connected PV system [4]. For residential prosumers, near-term economic benefits from meeting all or some of their demand through their on-site PV generation is as important as the long-term benefits. For countries where the feed-in-tariff is implemented near-term economic benefits can be assessed by Prosumer Electricity Unit Cost (PEUC), a parameter previously introduced by the authors [4], which is defined as:

$$PEUC = \frac{TAC+GP-FITR1-FITR2}{TEC} \qquad (1)$$

Where TAC is the total annual cost of the system which is composed of annualised investment and operation and maintenance costs; GP is the annual cost of electricity purchased from the grid by the prosumer; FITR1 and FITR2 are the FIT incomes that the prosumer receives for PV generation and export of surplus generation to the grid, respectively; TEC is the total energy consumed by the prosumer annually. In the PEUC definition near-term is defined as the first year of operation. Evidently, both the near-term and the long-term financial returns from a PV system, assessed in terms of PEUC and NPV or LCOE respectively, depend on the energy yield from the system. A variation in the energy yield will alter the economic performance of the system and consequently the investment attractiveness of PV systems to possible prosumers.

1.2 Impact of grid integration on annual energy yield

Grid integration of residential PV systems is a multifaceted problem involving the electricity distribution network operator (DNO), PV system, the prosumer and the policy regulator. The primary technical objective of the DNO is to deliver high-quality, safe, and reliable electric power to its customers (residential, industrial, commercial, etc.). Distribution networks were originally developed on the assumption that electricity flows in one direction, from the generation side (usually large power plants) to the load side. Distributed Generation (DG) technologies like PV systems are connected to the distribution side of the power network and this may result in a reverse power flow (i.e. in a direction opposite to that of the conventional power flow). The impacts of integrating PV to the grid can be twofold: the first is the impact of PV systems on the grid performance and the second is the impact of the grid events (including those caused by PV systems) on the performance of PV systems. Many researchers have looked at the impact of PV systems on the grid in terms of voltage regulation, losses, harmonics and resonance, fault levels and protection, stability etc. [5]. However, the effects of grid events on PV system performance (and hence energy yield) are often underestimated [6].

The energy yield from a grid connected PV system depends on the distribution network capacity, the demand profiles and the penetration level of PV or other renewables in the network in addition to the meteorological conditions [7]. As the level of PV penetration increases, at times of high generation and low demand network voltage may rise beyond the statutory limit due to reverse power flow [8]. In the UK, Engineering Recommendation G83/1 requires that PV systems connected to the low voltage (LV) distribution networks are disconnected from the grid when the voltage at the point of their connection to the LV network exceeds 1.1 p.u. [9]. The disconnection requirements vary amongst different countries, for example in Germany conventional generation currently has to yield in favour of renewable energy. A voltage rise will therefore result in curtailing of PV generation and in so doing reduce the PV energy yield.

A summary of the factors that affect PV energy curtailment is given in Fig. 1. The energy capture from a grid connected PV system and consequently curtailment depends on the inverter and the network capacities. PV inverters in westerly climates like that of the UK are often de-rated to reduce costs and improve efficiency as the modules generate their peak kW output only for a short time during the entire year [10]. The reliability of the inverter technology also influences the energy yield. At any instant the original network installed capacity may not be fully available to host PV generation. The capacity will depend on the topology of the network and the demand, the presence of other DGs and their generation and the presence of active network control elements such as on load tap changing transformers and their operation.

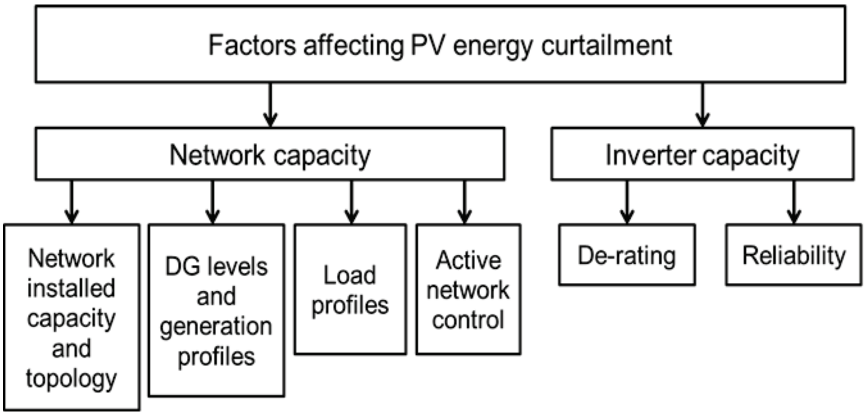

Fig. 1 Factors affecting PV energy curtailment

Previous studies have considered the impact of meteorological conditions on the energy yield of PV systems [11] and the impact of PV systems on the grid operation. However, an assessment of the impact of grid events on the PV system in the context of energy yield has not previously been undertaken.

1. 3. Development of an algorithm to estimate PV energy yield under grid-connected operation

The problem of estimating renewable energy curtailment under a high level of penetration is an important one and has been discussed in [12] which looked at the wind energy curtailment in Ireland. As the PV penetration in the UK has grown at a fast rate since the introduction of feed-in tariffs in 2010, there is a need for development of methodologies to investigate the impact of the distribution network on the annual energy yield from PV systems. There needs to be an algorithm which takes into account PV generation and prosumer load profiles. For the benefit of potential PV prosumers and decision makers (possible end users) the algorithm should be (1) efficient in terms of computational resources, (2) easy to implement, (3) able to consider a range of PV penetration scenarios and (4) able to deal with PV generation and prosumer load profiles having different resolutions.

Fig. 2 shows a block diagram of the algorithm proposed to meet these targets. For the same network, different scenarios can be simulated by varying the PV penetration level, demand profile and PV generation profiles. PV generation profiles, network configuration and demand profiles are the inputs to the algorithm. Voltage profiles for all nodes of the network, for the PV penetration level considered, are calculated by the algorithm based on load flow. PV systems are required to shutdown at nodes where voltage limits are violated, which results in curtailment of PV energy. In the next step of the algorithm, nodes with voltage limit violations are identified and PV energy curtailment is quantified. The energy yield estimates are then determined, for PV systems at all nodes, by subtracting their respective curtailment from the energy yield.

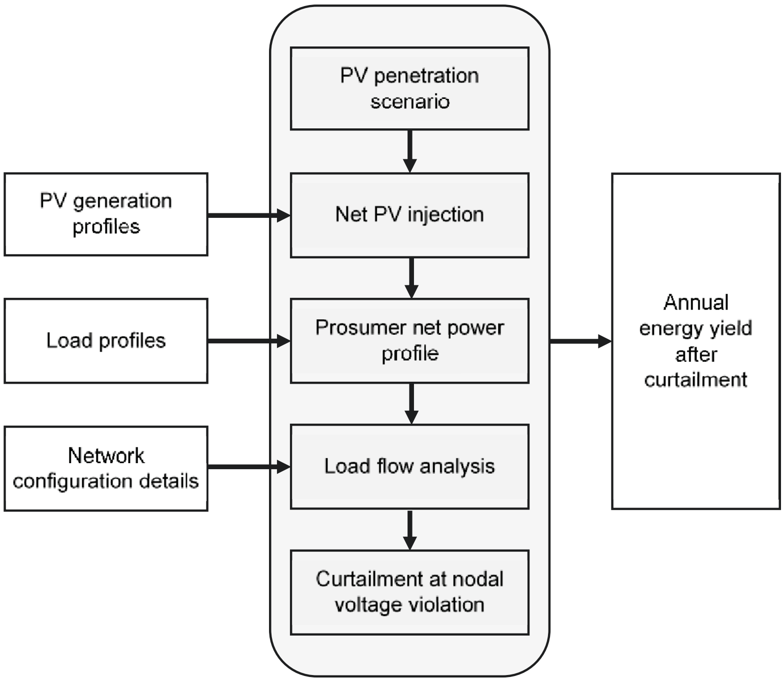

Fig. 2 Proposed energy yield estimation algorithm

1.4 Aims

This study aims to evaluate the effect of distribution network on the annual energy yield and economic performance of residential PV systems under increasing PV penetration levels; a case study was created for Newcastle upon Tyne with a generic UK distribution network model. With the aid of the proposed energy yield estimation algorithm this study aims to: (1) identify penetration levels at which PV generation curtailment as a consequence of network voltage rise beyond grid limits occurred, (2) analyse the variation in the percentage of annual energy yield curtailed among the systems connected to the network, (3) investigate the volatility of economic performance of the systems depending on their location within the network (nodal sensitivity), and (4) evaluate the impact of the resolution of PV generation profiles (in techno-economical terms, a statistical analysis is not intended) on energy yield estimates and consequently economic performance for the case study created for Newcastle upon Tyne.

2. Research Methodology

2.1 PV system design and simulation

The UK government promotes the adoption of PV systems by means of the Feed-in Tariff (FIT) scheme for systems below 50 kW. FIT is a two-part incentive payment for energy generated by PV systems. A generation tariff is paid for the entire PV energy generated while an export tariff is paid only for energy exported to the grid. The average installed capacity of residential PV systems under the highest FIT category is about 3 kW [13] and therefore, this size was chosen in this study for ease of simulation. This assumption does not affect the direction of this study and the conclusions. The module technology chosen is crystalline silicon since it is the most mature PV technology and has a market share of 80-90% [14]. The system configuration chosen is twelve 250 W poly-crystalline modules (3 kW in total) connected in series to a 2.5 kVA inverter.

Typical PV systems were modelled in PVSyst [15], for simulating hourly PV energy outputs for a typical year and thus determining the annual PV generation. As it is the most up-to-date public domain database for Europe, PVGIS climate-SAF was selected as the reference solar database for the UK [16]. The simulation studies were based on the following assumptions: (1) all systems are of the same size and technology, (2) all systems have optimum design for the location i.e. the system has optimum tilt, south facing array and optimum inverter to array de-rating, (3) the effect of shadowing is not considered and (4) storage is not considered.

2.2 Prosumer's demand

The electricity demand of a residential consumer depends on a number of factors, such as the number of occupants at the residence, age, lifestyle habits and the quantity and nature of electrical devices [17]. A smart meter electricity trial was undertaken in the North-East of UK (2012-14) as part the Customer Led Network Revolution (CLNR) project [18]. Hi-resolution metering was conducted at selected customer premises. The resulting load profile data sets are free to download from the project website [18]. Since the residential type load profile data from CLNR project is representative of different residential house types, family sizes and occupancy patterns, they were used as the prosumer load profile data for this study. The authors trust the data to be of sufficient accuracy. As it is not the focus of this work an uncertainty analysis on the data was not considered. However, the impact data uncertainty could have on the results will be discussed in section 3.2.

2.3. Network Modelling

The typical UK distribution network model [19] used is shown in Fig. 3. A 33/11 kV substation with two 15 MVA transformers supplies six 11 kV outgoing feeders and each 11 kV feeder in turn supplies eight 11/0.4 kV substations. To simplify the analysis, only one 400 V feeder from an 11/0.4 kV substation, supplying 384 houses through four 400 V outgoing radial feeders, was modelled in detail. The other feeders together with their connected loads were represented as individual lumped loads connected to the respective 11/0.4 kV substations. Therefore, the total load connected to an 11 kV feeder is equivalent to that of 3072 (= 8 × 384) houses and the total load supplied by the 33/11 kV substation is equivalent to that of 18432 (= 6 × 3072) houses.

2.4. Load flow

A voltage rise beyond grid limits results in the curtailment of PV generation at a node. In order to calculate the voltages at all nodes of the distribution network model considered for a particular load/ generation condition it is essential to incorporate a suitable load flow method in the energy yield estimation algorithm. Considering daily PV generation / load profiles at a resolution of 30 minutes, there would be 48 load/ generation states which translates to running the load flow 48 times. For 365 days (i.e. for the annual energy estimate), at a daily resolution of 30 minutes load flow has to be run 17520 (= 365 x 48) times. In practice, the available resolution of PV generation and load profile may not be as high. However, the number of load flow runs required may still might be in thousands. For this reason, it is necessary to have a simple and computationally efficient load flow method. Because of its flexibility and ease of use MATLAB/Simulink was chosen for modelling. Analysis of the dynamic variation of PV penetration at select nodes was not considered in this work as it is a much larger topic and most literature [20] in this research area point to the need of intelligent mechanisms for the choosing which PV system should be curtailed.

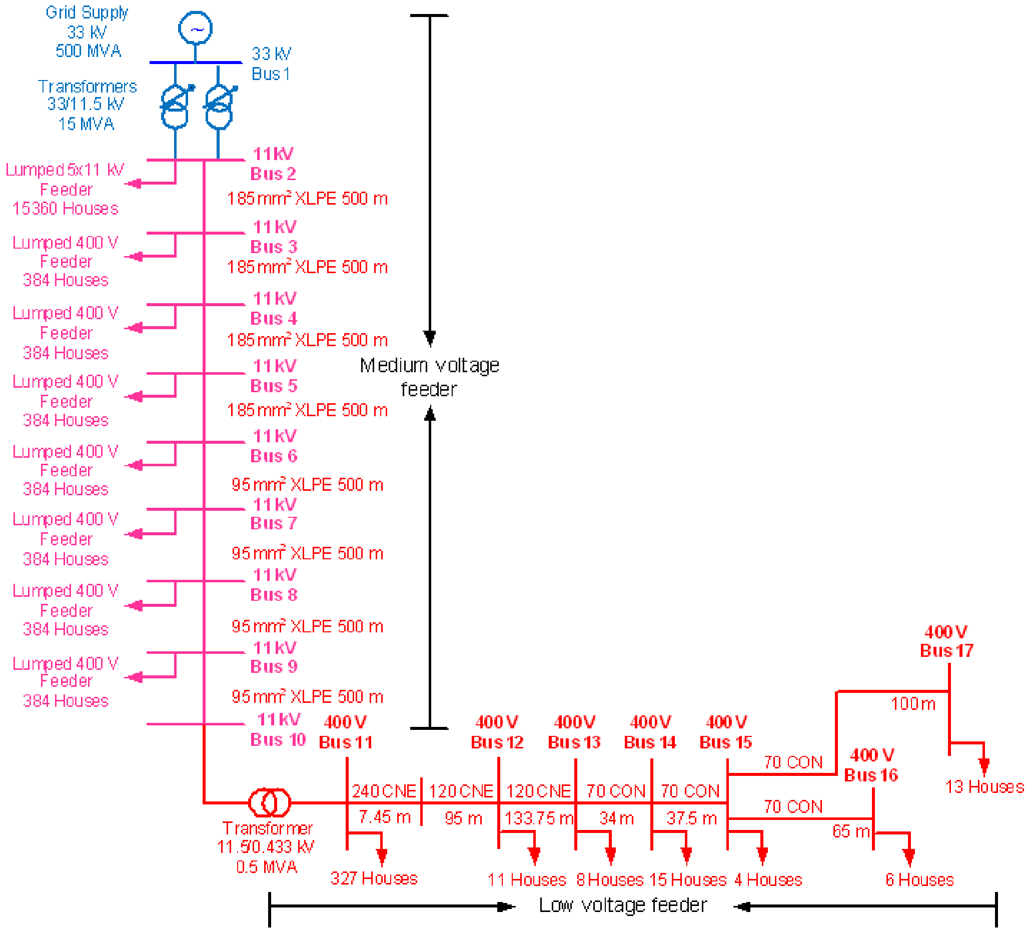

Fig. 3 Typical UK distribution network with one LV feeder shown in detail [19]

2.4.1 Simulink model

Initially the model of the distribution network as described in section 2.3 was built in Simulink. Load profile and PV generation profile for a single summer day from [21] having a resolution of 1 hour was used to observe the computation time taken. Given the resolution, assuming every house in the network has a PV system, 24 simulation runs were required. For an Intel core i7 2.2 GHz computer with 8GB of RAM running MATLAB/Simulink 2015, simulations took between 1 and 3 minutes depending on prosumer's net power injection for that run. It took 28 minutes to simulate the entire day. Assuming the same daily duration it was estimated that it will take 170 hours and 20 minutes to simulate a complete year so that annual energy yield post any curtailment can be calculated.

2.4.2 MATLAB distribution load flow

In order to reduce the computation time, and to able to consider a range of PV penetration scenarios in parallel a program was written in MATLAB. The Distflow distribution load flow algorithm for radial networks [22, 23] was chosen. As the mitigation of unbalance is a key step dealt with in the power distribution planning process, a balanced system is assumed, so a “Per Phase” analysis was used. However the magnitude of unbalance and its propagation will be For a radial distribution network comprising of n buses as shown in Fig. 4, Distflow involves the following recursive formula to find the active power, reactive power and voltage at each branch on the feeder [22]:

$$P_{i+1} = P_i - r_{i+1}\frac{P_i^2+Q_i^2}{V_i^2} - P_{Li+1} \quad (2)$$

$$Q_{i+1} = Q_i - x_{i+1}\frac{P_i^2+Q_i^2}{V_i^2} - Q_{Li+1} \quad (3)$$

$$V_{i+1}^2 = V_i^2 - 2(r_{i+1}P_i + x_{i+1}Q_i) + \frac{(r_{i+1}^2+x_{i+1}^2)(P_i^2+Q_i^2)}{V_i^2} \quad (4)$$

Where P_i, Q_i are the active and reactive power flows at the sending end of bus i+1, V_i the magnitude of the bus voltage at node i. Lines are represented by series resistance r and reactance x. P_L and Q_L are the active and reactive power consumed by the load at the bus. It is assumed that the substation bus voltage V_0 is always constant.

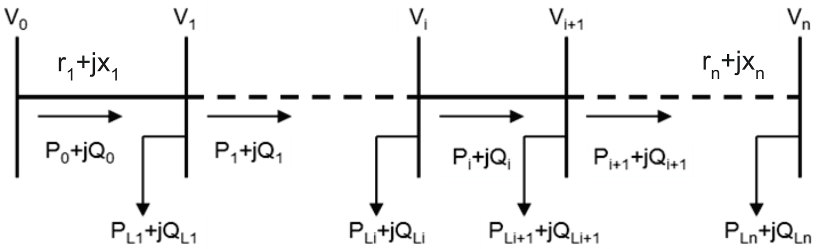

Fig 4. Representative diagram of radial distribution network parameters

The MATLAB program developed was run on the same computer for the single summer day’s load and PV generation conditions described (for observing the computation time) in section 2.4.1. The simulation run took less than 5 seconds. Fig. 5 shows the correlation between the Simulink model and the MATLAB algorithm for the 24 hourly voltages at the most sensitive node (bus 17). The value of R^2 coefficient was 0.83 indicating a very good agreement.

2. 5. Post-Curtailment Energy Yield Estimation (PCEYE) algorithm

The computational sequence for scenario based post-curtailment annual energy yield estimation is as depicted in Fig. 6. Distribution network parameters, load profiles and PV generation profiles are the inputs to the algorithm.

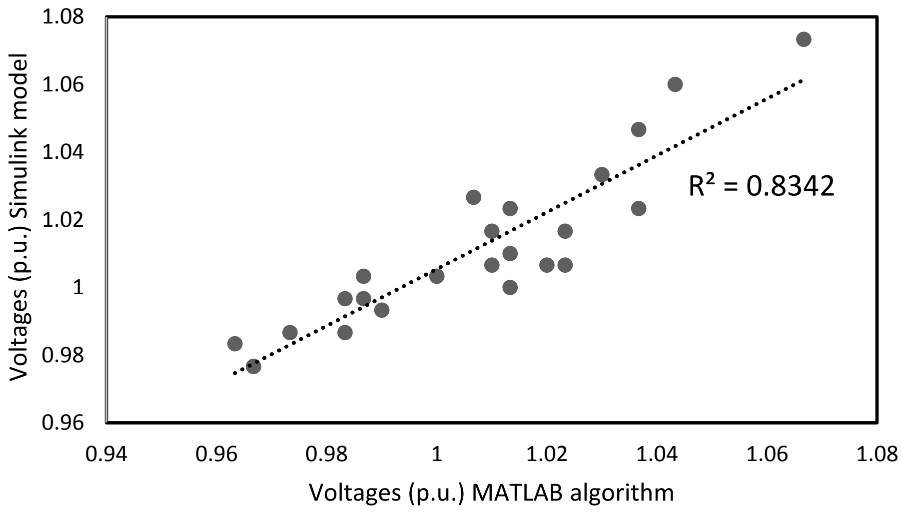

Fig. 5 Correlation between the distribution network voltages obtained using the Simulink model and the MATLAB algorithm

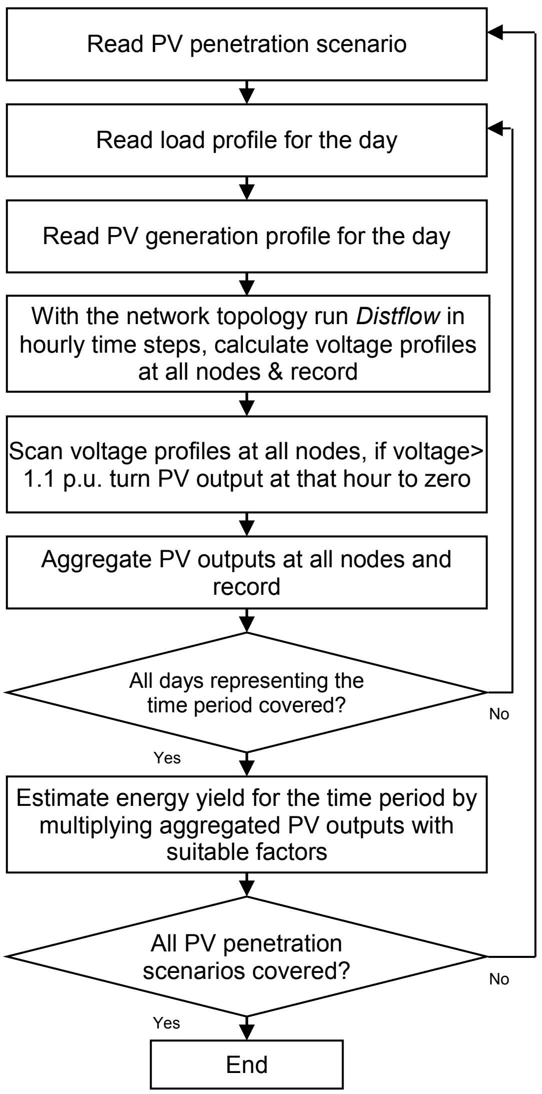

Fig. 6 A flowchart of the post -curtailment energy yield estimation algorithm

Load profiles are assigned to buses based on the number of customers at the bus. PV generation is assigned according to the PV penetration scenario. Voltages at different nodes of the distribution network corresponding to the PV penetration scenarios are then calculated. A PV power curtailment event was considered when the voltage rose beyond the statutory limit (1.1 p.u.). The calculation is performed for all representative days of the time period, which can be in multiples of a day e.g. a day, a week, a year etc. Losses in PV system energy yield during the time period considered, due to power curtailment in response to voltage rise under the operating scenario, is estimated by applying suitable multiplication factors. There are two multiplication factors: The first one is the number of days of the time period with the specified load profile and second is the number of days of the time period with the specified PV generation profile.

At the end of the *Distflow* (for every hour), the results of voltages at all nodes are checked, if any of them is found to exceed 1.1 p. u., the PV generation at that node for that hour is counted as zero while calculating the daily energy yield of a PV system at that node. To produce an estimate of the annual energy yield post-curtailment, the daily energy yields are summed and multiplied by suitable factors to form the monthly energy yield. The monthly energy yields are then summed up to give the annual energy yield. The network's PV generation hosting capacity, i.e. the penetration level beyond which voltage rise and PV power curtailment occurs in the studied network, can be estimated by varying the PV penetration levels at the MV and LV network.

2.6 Economic performance analysis

PEUC described in section 1.1 was used in this study to analyse the sensitivity in economic performance of prosumers' PV systems, depending on their point of connection within the network. For any scenario considered, the prosumers annual cost of electricity is the product of their annual electricity demand and PEUC for that scenario. The data used in this work for economic performance analysis based on sources described in [24] is shown in Table 1.

Table 1. Data for economic performance analysis

Description	Value
System cost (£)	7000
Project term (years)	20
Interest rate (%)	4
Grid electricity price (£/kWh)	0.18
Generation tariff, FIT1 (£/kWh)	0.0432
Export tariff, FIT2 (£/kWh)	0.0491
Prosumer annual energy demand (kWh)	3600

2.7 Scenarios

In this study, the level of PV penetration is defined as the ratio of the number of houses with a PV system to the total number of houses in that section of the distribution network, with each PV system assumed to be 3 kW in capacity. In order to identify penetration, the levels at which PV generation curtailment as a consequence of network voltage rise beyond grid limits occurred and analyse the variation in annual energy yield curtailed among the systems, the following incremental PV penetration scenarios were considered for the case study of Newcastle upon Tyne:

- None of the houses have a PV system; i.e. 0% PV penetration in the network.
- PV penetration in the 11 kV network and the detailed 400 V feeder increased in steps of 10% from 10 to 100% as shown in Table 2.

Table 2. PV profile classification for analysis based on temporal resolution

		% PV penetration level in 11kV network									
		10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
% PV pnetration level in the detailed 400V feeder	**10**	S(10,10)	S(10,20)	S(10,30)	S(10,40)	S(10,50)	S(10,60)	S(10,70)	S(10,80)	S(10,90)	S(10,100)
	20	S(20,10)	S(20,20)	S(20,30)	S(20,40)	S(20,50)	S(20,60)	S(20,70)	S(20,80)	S(20,90)	S(20,100)
	30	S(30,10)	S(30,20)	S(30,30)	S(30,40)	S(30,50)	S(30,60)	S(30,70)	S(30,80)	S(30,90)	S(30,100)
	40	S(40,10)	S(40,20)	S(40,30)	S(40,40)	S(40,50)	S(40,60)	S(40,70)	S(40,80)	S(40,90)	S(40,100)
	50	S(50,10)	S(50,20)	S(50,30)	S(50,40)	S(50,50)	S(50,60)	S(50,70)	S(50,80)	S(50,90)	S(50,100)
	60	S(60,10)	S(60,20)	S(60,30)	S(60,40)	S(60,50)	S(60,60)	S(60,70)	S(60,80)	S(60,90)	S(60,100)
	70	S(70,10)	S(70,20)	S(70,30)	S(70,40)	S(70,50)	S(70,60)	S(70,70)	S(70,80)	S(70,90)	S(70,100)
	80	S(80,10)	S(80,20)	S(80,30)	S(80,40)	S(80,50)	S(80,60)	S(80,70)	S(80,80)	S(80,90)	S(80,100)
	90	S(90,10)	S(90,20)	S(90,30)	S(90,40)	S(90,50)	S(90,60)	S(90,70)	S(90,80)	S(90,90)	S(90,100)
	100	S(100,10)	S(100,20)	S(100,30)	S(100,40)	S(100,50)	S(100,60)	S(100,70)	S(100,80)	S(100,90)	S(100,100)

2.7 Data resolution

Most common weather databases used for PV system simulations, such as US Department of Energy [25], provide one data set per month at an hourly resolution for a typical year. For load profiles, it is usual to have one data set per season (spring, summer etc.) at an hourly resolution [4]. However, with the advent of the smart grids movement and consequently smart metering, the load profile data resolution has started to increase. Monthly data sets (instead of seasonal) have become available [26]. For CLNR residential customer data sets there were 7 load profiles with half hourly resolution representing the days of a week for every month of the year. This was the best temporal resolution available for load profiles of north-east England.

Usually, solar data from common weather databases are used as input to PV system simulation software to generate PV generation profiles (which are representative of the monthly average). However, for this study the climate-SAF database provided daily solar data for a typical year. For an optimally designed 3 kW residential grid-connected PV system in Newcastle upon Tyne, PVSyst [27] simulations resulted in 365 realistic daily PV generation profiles at an hourly resolution. To represent the temporal resolution of common available PV generation profiles monthly averaged PV generation profiles were created by averaging PVSyst hourly outputs. Thus, to investigate the impact of temporal resolution of PV generation profiles on post-curtailment energy yield estimates, PV generation profiles were classified into two types as shown in Table 3. A number of research studies have been published on the impact of temporal resolution of input data on renewable energy simulations [28]. However, they were all statistical analyses and the focus was not on energy yield and the impact of the grid on this.

Table 3. PV profile classification and data resolution

Description	PV data title	No. of PV Generation Profiles	No. of Load Profiles	No. of data points per profile
Base case	Monthly averaged	12	12 x 7 = 84	24
High-res	Daily	365	12 x 7 = 84	24

3. Results and Discussion

The use of monthly averaged PV generation profiles was considered as the base case. For the high-resolution case, i.e. with daily PV generation profiles, simulation and analysis was conducted based on the insights drawn from the base case.

3.1 Scenarios of PV generation curtailment

For the distribution network described in section 2.3, the voltage at each node is calculated for the base case (with resolution indicated in first row of Table 3). The amount of prosumer PV energy to be curtailed as consequence of voltage rise above the statutory limit at any node is then estimated for different PV penetration scenarios based on which post curtailment annual energy yield estimates were generated. Buses at the far end of the LV feeder are the most sensitive ones where voltage rise events occurred. Results showed that voltage rise occurred in the sensitive buses only at very high PV penetration levels of 90% or greater in both MV (11 kV) and LV network sections. Table 4 shows the PV penetration scenarios (from Table 1) where a reduction in energy yield occurred due to curtailment. With

100% penetration in the MV network, voltage rise was observed in the LV network even when it had only 30% PV penetration level. This sensitivity arises because of the upstream PV production and the LV feeder being at the far end of the network. The buses at the end of the LV feeder numbered 16 and 17 (see Fig. 3) were the most sensitive to changes in PV penetration levels. This is in agreement with previously published research [29].

Table 4. Base case PV penetration scenarios where curtailment occurred

Sl. No.	Scenario	% PV penetration in MV network	% PV Penetration in LV network
1	S(90,90)	90	90
2	S(90,100)	90	100
3	S(100,30)	100	30
4	S(100,40)	100	40
5	S(100,50)	100	50
6	S(100,60)	100	60
7	S(100,70)	100	70
8	S(100,80)	100	80
9	S(100,90)	100	90
10	S(100,100)	100	100

For the year considered in this work, the month of May had the highest average monthly PV generation for Newcastle. Fig. 7 shows the generation profile of the peak PV generation day which also occurs in May. High grid voltages occur under low demand conditions. The load profile for Wednesday in May (when the average demand is lowest) and the monthly averaged PV generation profile for May is also shown in this figure.

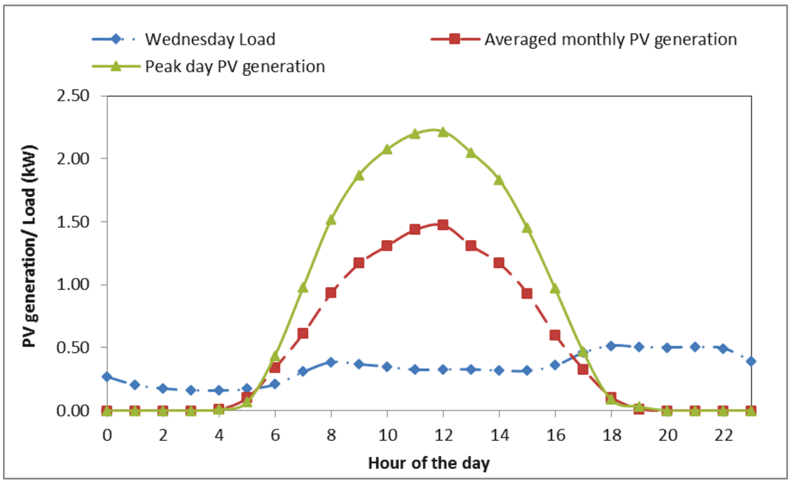

Fig. 7 Profiles of maximum PV generation and minimum demand profiles in the month of May for Newcastle upon Tyne

Figs. 8 shows the base case voltage profiles at each node along the LV feeder with 100% PV penetration in both MV and detailed LV feeders (scenario S(100,100)) for the monthly averaged PV generation profile and load profile shown in Fig. 7. As mentioned earlier, buses 16 and 17 are the most sensitive buses. Since their simulation results are identical, only bus 17 is mentioned from this point onward. Fig. 9 shows the voltage profile for bus 17 for the daily PV generation and load profiles shown in Fig.7 for the scenario S(100,100). A variant of the scenario simulated with the PV penetration at bus 17 set to zero also resulted in the same voltage profile due to the relatively small number of houses at the bus.

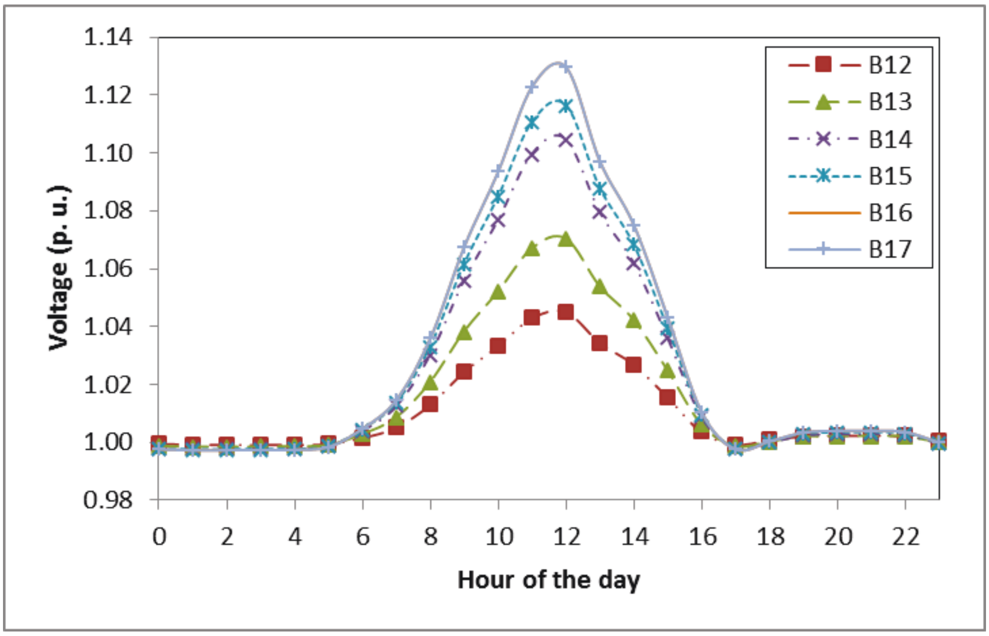

Fig. 8 Voltage profile along the 400 V feeder for an average Wednesday in May for PV penetration scenario S(100,100)[1]

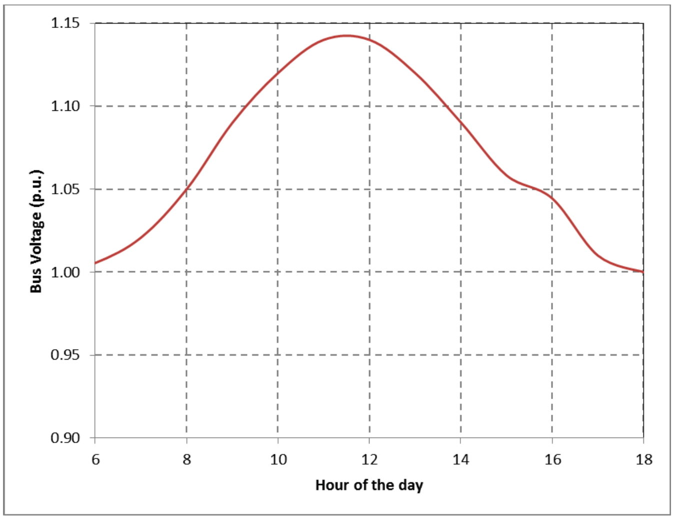

Fig. 9 Voltage profile at the bus 17 with daily PV generation profile

[1] In the legends of Fig 8 ‘B’ is an abbreviation for ‘Bus’, e.g. B12 stands for Bus12. The voltage profiles of B16 and B17 are coincident.

It can be noticed that in both cases the voltage rises above the 1.1 p.u. limit for the scenario shown. The rise in voltage and the duration of voltage rise is greater with the daily PV generation profile as can be seen from Fig. 9. It was observed from CLNR load dataset that, the demand is minimum between 10:00 and 15:00 for most part of the year. Thus, it can be concluded that, even under lower levels of PV penetration, during peak PV generation days the chances of voltage rise above statutory limits and consequent PV energy curtailment is high. Therefore, as for the base case, PCEYE was run to estimate prosumer energy yields for all scenarios of Table 1 with high-res case PV data. Unlike for the base case, there were 49 PV penetration scenarios (from Table 1) where a reduction in energy yield occurred due to curtailment as listed in Table 5. For convenience, 7 out of the 49 scenarios, highlighted in grey in Table 5 were chosen for detailed analysis. These scenarios had the same penetration level in both the MV and the LV networks. Fig. 10 shows the voltage profiles at the most sensitive bus (Bus17) for the peak PV generation and low demand day (in May) for these chosen scenarios. It was noted that voltage rise due to PV generation stays within 1.1 p.u. until the 40% PV penetration level. Beyond 50%, the voltage rises beyond limits and PV energy curtailment results.

It can be noted that the voltage exceeds 1.1 p.u. between 9:00 and 16:00. Without any control measures like Demand Side Management (DSM), the default setting for PV inverters is to turn off when node voltage exceeds 1.1 p.u. which will lead to a large PV energy loss for all PV systems connected at Bus 17 and possibly others. In this case, PV systems at buses 12-17 were affected by curtailment (unlike buses 14-17 for the base case), with bus 17 being the most severely affected.

Table 5. High-res case PV penetration scenarios where curtailment occurred

		% PV penetration level in 11kV network						
		40	**50**	**60**	**70**	**80**	**90**	**100**
% PV pnetration level in the detailed 400V feeder	**40**	S(40,40)	S(40,50)	S(40,60)	S(40,70)	S(40,80)	S(40,90)	S(40,100)
	50	S(50,40)	S(50,50)	S(50,60)	S(50,70)	S(50,80)	S(50,90)	S(50,100)
	60	S(60,40)	S(60,50)	S(60,60)	S(60,70)	S(60,80)	S(60,90)	S(60,100)
	70	S(70,40)	S(70,50)	S(70,60)	S(70,70)	S(70,80)	S(70,90)	S(70,100)
	80	S(80,40)	S(80,50)	S(80,60)	S(80,70)	S(80,80)	S(80,90)	S(80,100)
	90	S(90,40)	S(90,50)	S(90,60)	S(90,70)	S(90,80)	S(90,90)	S(90,100)
	100	S(100,40)	S(100,50)	S(100,60)	S(100,70)	S(100,80)	S(100,90)	S(100,100)

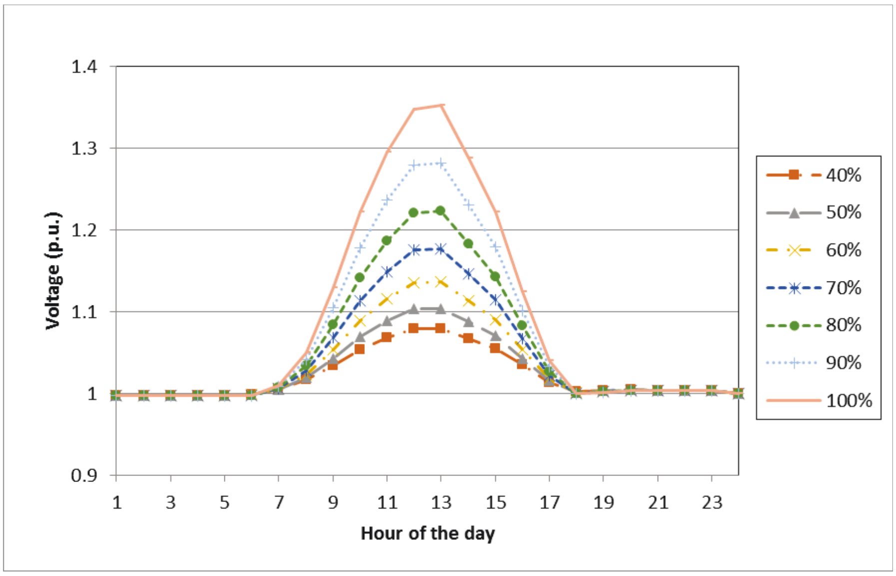

Fig. 10 Voltage profiles at bus 17 for the peak PV generation-low demand day

Fig. 11 shows the monthly variation in aggregate PV energy curtailment in the detailed LV feeder for the 7 PV penetration scenarios chosen for the high-res case. It can be seen that summer months have higher curtailment, with May having the highest curtailment, while winter months have generally lower curtailment, with December having the lowest amount of curtailment.

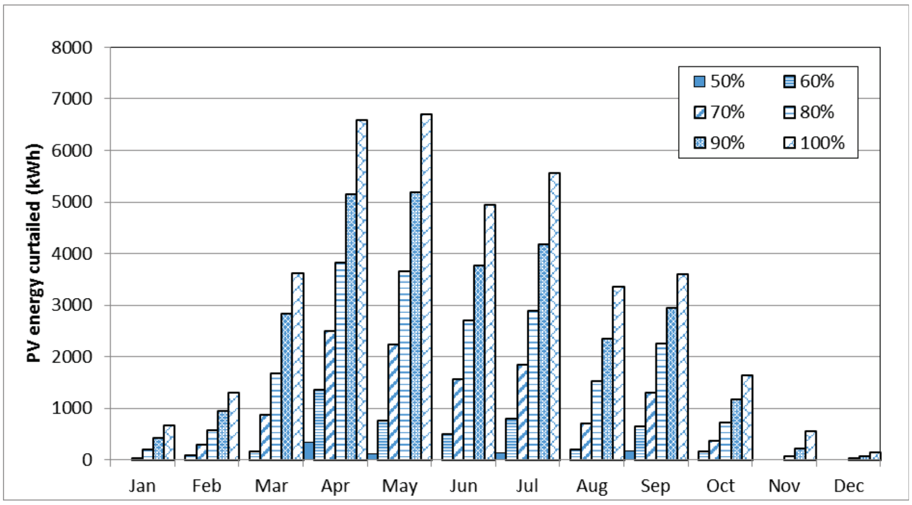

Fig. 11 Monthly variation in aggregate PV energy curtailment in detailed LV feeder

3.2 Impact of temporal resolution on curtailment

For prosumers located at different nodes on the LV network a curtailment ratio (CR) can be defined as the ratio of the PCEYE annual energy yield estimates to the un-curtailed energy yield. The maximum value possible for CR is 1, indicating no curtailment. The PVsyst annual energy yield for a typical PV system in Newcastle is 2651.3 kWh. Table 6 shows the CRs for the buses where curtailment was observed for the base case. It is observed that for the base case with monthly averaged PV generation profiles, the annual energy yield estimates would depict a loss only from Bus 14 towards the end of the LV feeder. The highest loss was incurred by PV systems at the end of the LV feeder (Bus 16 and Bus 17). PV systems closer to the MV source in terms of their point of connection in the network had lower losses in energy yield. This is under the assumption that the On Load Tap Changer (OLTC) operates to keep the MV substation at constant voltage.

Table 6. Curtailment ratios for the buses with curtailment under different scenarios for the base case

Bus No.\ Scenario	14	15	16	17
S(90,90)	1	1	0.9972	0.9972
S(90,100)	1	1	0.9845	0.9845
S(100,30)	1	1	0.9944	0.9944
S(100,40)	1	1	0.9845	0.9485
S(100,50)	1	1	0.9769	0.9769
S(100,60)	1	0.9944	0.9747	0.9747
S(100,70)	1	0.9845	0.9747	0.9747
S(100,80)	1	0.9769	0.9747	0.9747
S(100,90)	0.9972	0.9747	0.9747	0.9747
S(100,100)	0.9894	0.9747	0.9655	0.9655

Since averaging reduces the peaks in the PV generation profiles, using average values results in lower curtailment and gives smaller values for reduction in energy yield. Therefore, average PV generation profiles provide the most optimistic energy yield estimates. To comprehend the impact of averaging, results with averaged PV generation profiles have to be compared with those with daily PV generation profiles. Table 7 shows the CRs for the buses where curtailment was observed for the base case. It can be observed that the there is a large difference in CR for 100 % penetration level (scenario S(100,100)). The use of monthly averaged PV data was showing a loss of energy yield of less than 4% much lesser than the 39% reduction obtained with daily PV data. Since it is closer to actual operation, the results with daily high-res data are closer to reality. The high-res CR values with 50% PV penetration S(50,50) are lower than that for the 90% PV penetration scenario S(90,90) obtained with base-case (monthly averaged) PV data.

The results of the high-res study identify that, with increasing PV penetration levels, the grid has a significant impact on the energy yield from the PV systems. The annual energy yield values for the prosumer could be far different from what was provided by the PV system designer (or installer) at the time of installation despite similar weather conditions. This is an additional financial risk, one that most prosumers do not consider at the time of investing in

PV. The results also point to the impact of temporal resolution of PV data in estimating grid impacts and consequently investment decisions and policies.

Table 7. Curtailment ratios for the buses with curtailment under different scenarios for the high-res case

Bus No.\ Penetration level	**12**	**13**	**14**	**15**	**16**	**17**
50	1	1	0.9991	0.9973	0.9854	0.9854
60	1	1	0.9764	0.9519	0.9300	0.9300
70	1	0.9973	0.9185	0.8833	0.8434	0.8434
80	1	0.9683	0.8406	0.7982	0.7610	0.7610
90	0.9973	0.9147	0.7564	0.7181	0.6830	0.6830
100	0.9763	0.8362	0.6841	0.6485	0.6107	0.6107

Fig. 12 and 13 show the variation in annual aggregate PV energy curtailment in the detailed LV feeder with increase in PV penetration levels for the base case and the high-res case. It can be seen that for the case with PV generation profiles having daily temporal resolution, the network considered was able to host a PV penetration level of up to 40%, beyond which it needs to resort to curtailing the output from PV systems. The use of monthly averaged PV generation profiles (base case) was suggestive of a very high network hosting capacity. The results showed that the network could host PV generation without curtailment even at very high penetration levels (over 80%). Thus it can be observed that network hosting capacity estimates using distributed generation data with low temporal resolution (as in the base case) could be misleading. For the load profiles, the temporal resolution used for this study was restricted to what was available from the CLNR dataset (84 daily profiles for a year). However, by using synthetic load profile generation methodologies [30] it is possible to extend the resolution to 365 days if essential input data required for the methodology are available. The conclusions drawn from this analysis will not be much different with an improvement in the accuracy of CLNR data, considering the magnitudes of load profiles, voltage limits and other network parameters.

3.3 Analysis of economic performance

In order to investigate the volatility of economic performance of the systems depending on its location within the network, PEUC was calculated for prosumers at each bus with CR less than 1 (i.e. curtailment occurred) for the base case and high-res scenarios previously discussed. For comparison of the impact of temporal resolution, PEUC and annual cost of electricity for prosumers at the most sensitive bus (Bus 17) are shown in Table 8 and 9. It can be observed from Table 9 that there is a significant increase in PEUC with higher penetration. The use of low resolution data (base case) only shows a slight increase in PEUC, giving an increase of £15.56 in the prosumer’s annual electricity cost even with 100%

PV penetration in the network. This is not a significant investment risk and most prosumers would not be worried. However, an increase of £156.74 (at 100% penetration high-res case) is a significant investment risk and worry to most prosumers.

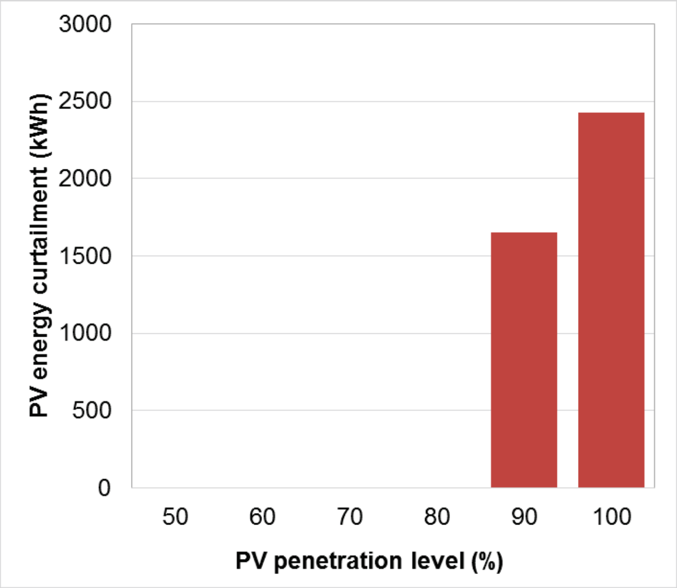

Fig. 12 Annual aggregate PV energy curtailment in detailed LV feeder for the base case

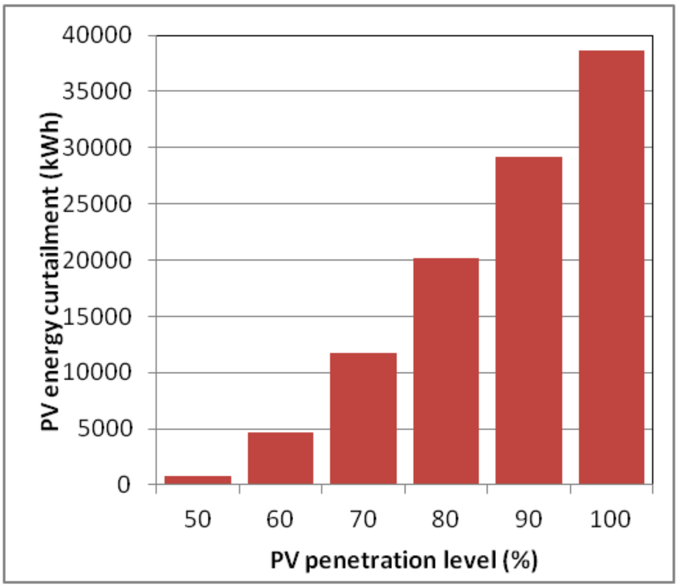

Fig. 13 Annual aggregate PV energy curtailment in detailed LV feeder for the high-res case

Table 8. Base case PEUC and annual electricity cost for prosumers at the most sensitive bus

Sl. No.	Case	Scenario	PEUC (£)	Annual electricity cost (£)
1	No curtailment		0.2055	739.76
2	Lowest curtailment	S(90,90)	0.2058	740.93
3	Highest curtailment	S(100,100)	0.2098	755.32

Table 9. High-res case PEUC and annual electricity cost for prosumers at the most sensitive bus

Sl. No.	Penetration level	PEUC (£)	Annual electricity cost (£)
1	50	0.2072	745.84
2	60	0.2136	769.03
3	70	0.2237	805.24
4	80	0.2333	839.73
5	90	0.2423	872.35
6	100	0.2507	902.58

With high PV penetration levels, there is not only an increase in investment risk due to lower income from PV generation but also a disparity in income distribution. Some PV system owners are more susceptible to low return on investment than others. As can be seen from Table 10, the annual electricity cost of prosumers at Bus 16/17 is increased by £156.74 whereas for prosumers at Bus 12 the increase is only £3.83. Thus prosumers at the buses farthest from the main substation are the ones most prone to a reduction in income from PV and consequently have higher investment risk. These prosumers have no say in the installation of PV or other DGs upstream. DNOs and policy makers should make policy decisions taking this possible income disparity into account. If data on the impact of the grid on their potential PV outputs are available, prosumers would be able to make a sound decision as to whether or not to invest in a PV system for their home.

Table 10. High-res case PEUC and prosumers annual electricity cost between buses for 100% PV penetration

Bus	PEUC (£)	Annual electricity cost (£)
12	0.2082	749.67
13	0.2245	808.27
14	0.2422	871.88
15	0.2463	886.77
16	0.2507	902.58
17	0.2507	902.58

Since FIT income is not received for the energy lost by curtailment, both the long-term and near-term economic viability of the prosumers is affected. This points to the necessity for adequate measures like the use of storage, active voltage control (AVC) [31, 32] and DSM to be put in place to enable the capture of maximum PV energy.

4. Conclusions

A computational algorithm easy on resources is developed in this work to evaluate the effects of distribution network on the annual energy yield of residential PV systems under scenarios of increasing PV penetration. Results with high-res PVGIS solar data for the case study of Newcastle, UK showed that, even for low PV penetration levels (50%), during peak

PV generation days, the chances of voltage rise above statutory limits and consequent PV energy curtailment is high. This is much different from the curtailment penetration level (90%) predicted with the monthly solar data. The monthly data was also misrepresenting the number of prosumers who would be affected and was suggestive of a very high network hosting capacity.

The results of the high-res study also identified that, with increasing PV penetration levels, the prosumers' annual energy yield and annual electricity costs could be far different from what they would have expected for the weather conditions. This is an additional financial risk, one that most prosumers do not consider at the time of investing in PV. There is also a disparity in income distribution, some PV system owners are more susceptible to low return on investment than other. DNOs and policy makers should include this possible income disparity into their policy considerations and should make potential prosumers aware of this disparity before they make investment decisions. In order to improve the economic viability of prosumers affected by curtailment adequate measures like the use of storage, active voltage control and demand side management could be put in place. The PCEYE algorithm can be a valuable tool to investigate the effectiveness of these control measures.

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