Scientific Research Publishing

Energy and Power Engineering, 2018, 10, 226-252
http://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

Economics of Pooling Small Local Electricity Prosumers—Prosumer vs Business as Usual Approach

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How to cite this paper: Kästel, P. and Gilroy-Scott, B. (2018) Economics of Pooling Small Local Electricity Prosumers—Prosumer vs Business as Usual Approach. *Energy and Power Engineering*, **10**, 226-252.
https://doi.org/10.4236/epe.2018.105016

Received: February 23, 2018
Accepted: May 28, 2018
Published: May 31, 2018

Abstract

This paper analyses the economics of pooling small UK based local electricity prosumers with back-up access to the National Grid and compares it to the current conventional UK electricity supply model—business as usual (BAU) approach. This is contextualized against the UK energy market framework, prosumer research and changing energy market dynamics. For the economic assessment a three-tiered production/supply and consumption model is developed based on site specific levelized cost of electricity (LCOE) and other cost parameter to operate the model. Modeling results indicated the economic feasibility and advantage of a prosumer approach in a significant number of modeling scenarios. Additionally, a break-even analysis for the two approaches was undertaken to understand the sensitivity of individual input parameters.

Keywords

Energy-Prosumer, Decentralized Energy, Economics, LCOE

1. Introduction

With the emergence of distributed energy resources (DER), the relevance of so-called "prosumers"—entities/households that are producer and consumer of energy in one—increases [1] [2]. There are different aspects in the context of energy markets and prosumers, which are researched, and which impact each other e.g. the definition of prosumer models and how they fit into the energy market; a highly regulated market framework and how it integrates new market entrants; how new technologies and their characteristics are adapted to; and the economic aspects of energy prosumers. The aim of the research is to provide a better understanding of the relevant factors influencing the economics of prosumer models and examine their role in the context to the UK and its electricity market framework.

Energy markets tend to be heavily regulated and are subject to political decisions. Such regulation is not only motivated by consumer protection but is also desired by utilities and investors to have a stable commercial framework for investments [3] [4] [5]. Political and regulatory frameworks influence market structures, hence guide economic activity and innovation [6] [7] [8] [9]. The current regulatory and technical framework is challenged with the emergence of renewable energy (RE), its specific characteristics and increasing prosumer penetration, e.g. capital intensity and low running cost, intermittence, decentralized application, natural resource dependent site selection criteria etc. [10]-[15].

The UK electricity market is divided along the following functional lines: 1) generation; 2) transmission; 3) distribution; and 4) supply. See **Figure 1** [16] [17] [18] [19]. The structure is designed to encourage competition mainly on the generation and supply level while grid activities are organized as regulated private monopolies [20] and limited consideration is given to prosumer models. The grid was initially designed to be a one-way system, which "only" delivers electricity to customers based on an anticipated load profile [21] [22] [23]. With the increasing popularity of DER, networks face new challenges as fed in energy from DERs might overstretch the network design and imply the necessity of network upgrades [23] [24] [25]. Grid operators improve their ability to increase network capacity and stability management and to integrate intermittent RE , e.g. real time generation monitoring and the ability to curtail generation, voltage control equipment, fault-ride-through mechanisms and to improve forecasting systems have been encouraged and incentivized or even made obligatory [21] [26].

Economic mechanisms like quota [26] [27] [28], Feed in Tariffs (FiT), market price plus premium, floor & cap systems [26] and flexibility premiums [29] have been developed to introduce competition and/or incentives to adjust to energy

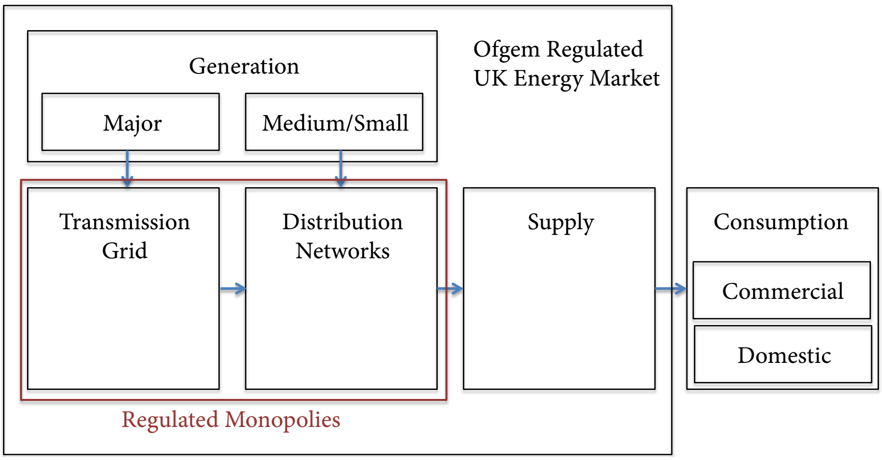

Figure 1. UK electricity market structure.

demand and providing a benign investment environment. Tveten *et al.* [30] assessed the merit order effect of PV in peak demand periods in the German electricity market and demonstrated that high PV penetration levels are not only crowding out fossil fuel based electricity but also resulted in reduced electricity prices, reduced price peaks and reduced price volatility [30].

Prosumers are a relatively new concept in energy markets but have been present in a wide range of other markets for a long time [31] [32] [33]. The common part is that prosumers (partly) produce and consume a product/service at the same time. At which stage and to what extend that happens can be quite different. Bremdal [34] identified value chains and value networks in which a prosumer will take on a specific role. In a value chain (inspired by the definition of Porter [35]) the consumer is engaged at the end of a production process and only finishes the product. In a value network (based on the theories of Stabell & Fjeldstad [36]) the process is much more interactive and the network itself is the market and its participants may produce for and consume from the network in real-time. See **Figure 2** for four prosumer business model types developed by Bremdal [34]. A decisive differentiator between those concepts is management and control of the product design and production process, with the value network representing the part of the spectrum with lesser centralized functions. [34]. Prosumer models have become more prominent and explicit with the emergence of the internet as enabling technology and its far reaching and interactive features [32] [37].

Most energy markets have not lent themselves to prosumer models so far. That is mainly due to the centralized nature and structure along the value chain and the economics of scale in conventional electricity generation. Nonetheless, increasing competitiveness of DER and the development in Information and

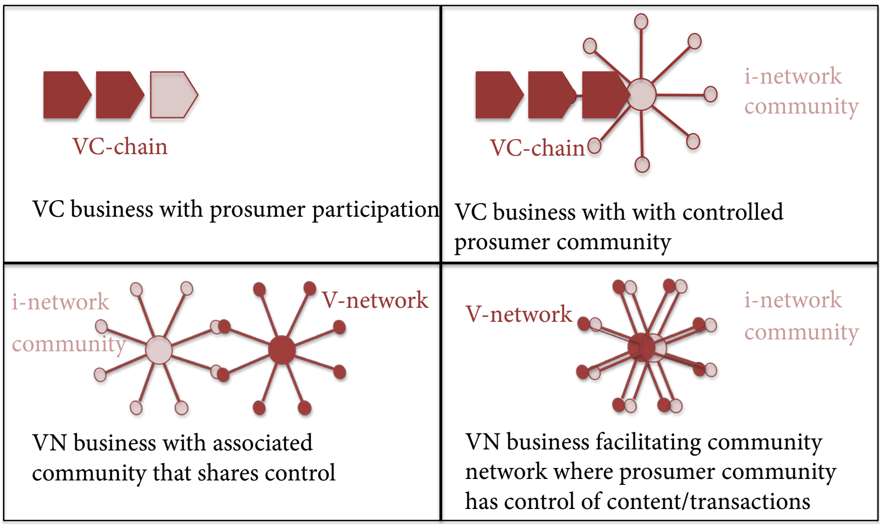

Figure 2. Archetypes of prosumer business models. Value Chain (VC) and Value Network (VN) models with different degrees of prosumer involvement and control over products. Specifically in the VN models, digital infrastructure providers who enable prosumer activity via information networks are a common feature [34].

Communication Technology (ICT), often associated with smart grid technology, are the basis for new opportunities [2] [33] [34] [38] [39]. The motivation for consumers to become prosumers in the energy sector broadly mirrors that of other markets, yet, the context of increasing energy prices and the drive towards green energy play prominent roles. The role of the prosumer is not only understood as purely producing and consuming energy but because of the generally non-storable nature of electricity, they are also active market participants [2] [33] [38] [39]. This stems from the fact that prosumers might supply to or demand electricity from the grid at random and this makes them exposed to electricity market prices and dynamics. This is where smart grid technology as a management and control tool is positioned. Smart grid technology can read price signals, facilitate Demand Side Management (DSM), control use of excess supply (e.g. selling it to the grid), can analyze weather forecasts etc. The exact role and dynamics of this technology is not clear yet and is part of extensive on-going research [33] [40]. At the same time RE is employed already and with it reaching grid parity, the economic benefit on a household level is already existent for prosumers [9] [39] [41] [42] [43]. This leads to increased efforts to develop business models on how to capitalize on the advantages of DER, e.g. direct deployment, prosumer community schemes or virtual power plants [2] [38] [39] [44].

In the context of the German Energiewende ("Energy Transition") the German government initiated in 2008, a 4-year long field research program called "E-Energy" with six subprojects focusing on DER, DSM and prosumer models. The main objective has been to show how optimization and use of ICT can help to achieve an economical solution, energy security and environmental compatibility [45]. The research showed significant saving potentials through increased transparency [22]; confirmed the technical feasibility of integrated prosumer models [46] [47] [48]; argued that the co-ordination of the regulatory framework, infrastructure adaption and consumer involvement is essential to succeed [49]; that tariff incentives can trigger load shifts [40] [50]; that connected grid cells could increase technical resilience, stability and flexibility [51]; and that different intermittent RE sources can be managed to positively contribute to supply security and more efficient network usage [52] [53] [54]. More recent international research in various prosumer related issues mirrors some of these results [2] [55] [56] [57] [58] [59].

2. Methodology

The methodology is designed to analyze the economics of pooling small local electricity prosumers in an actual or virtual micro-grid environment with back-up access to the National Grid ("Prosumer-Model" or "Prosumer-Approach"). The Prosumer-Model results are compared to the established electricity supply model or business as usual approach ("BAU-Model" or "BAU-Approach"). The economic advantage/disadvantage between the two approaches is measured as difference between the present value of the annual and lifetime cost for a given electricity consumption in British Pounds (£) ("Model"). **Figure 3** shows the schematic methodology approach taken. Input data of the Model are based on simulation results described in an earlier paper of the Authors which describes the site selection process, the LCOE and self-consumption level calculation [1]. See **Table 1** for the analyzed UK sites.

The Prosumer-Approach is based on three-tiered hierarchical production/consumption model to balance electricity demand at any point in time:

- level-1, the prosumers consume their own production;
- level-2, they share/provide excess production to or draw/consume additional demand from a member-energy-pool; and
- in level-3, they feed into or take electricity from the National Grid.

See **Figure 4** for a graphic representation. At each hierarchy level cost and income parameters are assigned resulting in the overall cost for the consumed electricity.

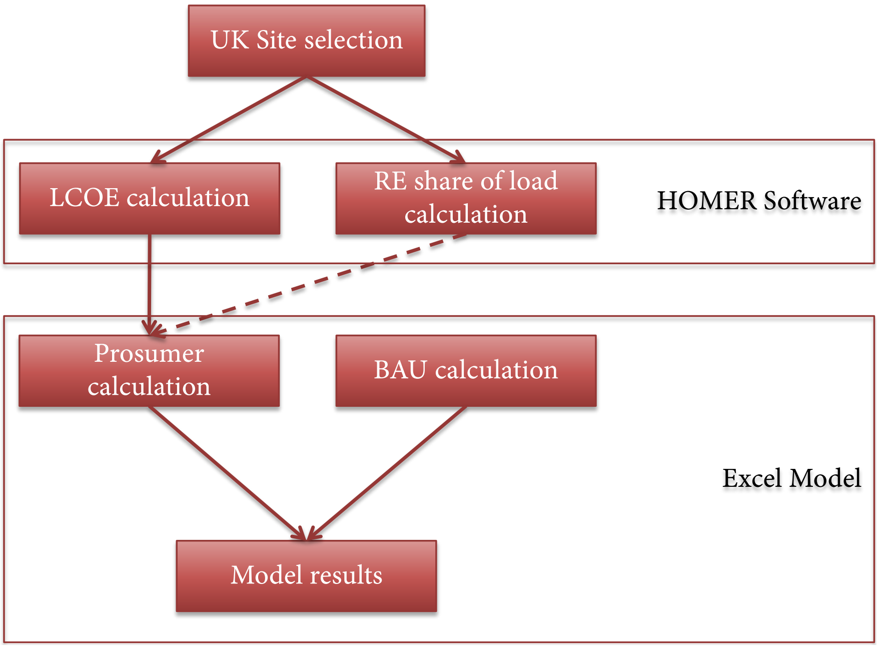

Figure 3. Schematic presentation of methodology approach. LCOE and RE share of load are based on the results of an earlier paper of the Authors [1].

Table 1. Selected UK sites. Postcodes will be used as site identifier.

Name	Postcode	Latitude	Longitude
Inverness	IV1	57'44' North	4'19' West
Carlisle	CA2	54'87' North	2'99' West
York	YO24	53'93' North	1'16' West
Aberystwyth	SY23	52'37'North	4'09' West
Kingston upon Thames	KT2	51'43' North	0'28' West
Camborne	TR14	50'19' North	5'24' West

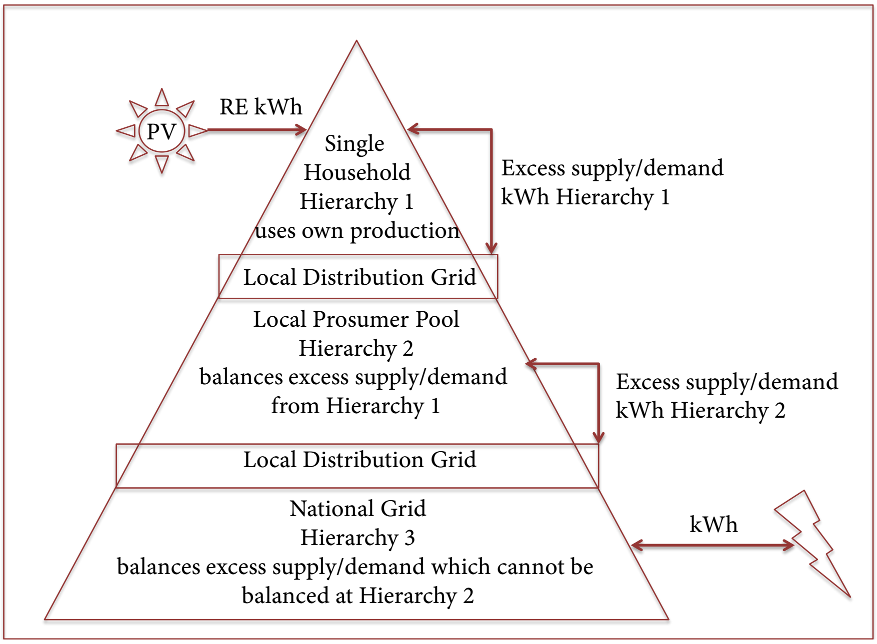

Figure 4. Graphic representation of the Prosumer-Model. Self-produced electricity is first directly consumed at household level, than shared at local prosumer pool level and as last resort the National Grid is used to balance any remaining excess supply/demand [1].

The Prosumer-Model is based on the assumptions that, firstly, it assesses the economics of a single prosumer only and secondly, that each prosumer produces exactly as much electricity as they consume in one calculation period, being one year. This results in a zero-sum balance over the three hierarchy levels.

The BAU-Approach calculates the annual electricity cost by multiplying the consumed energy with a price per kWh as it is the standard approach in today's market. In order to make it comparable with the assumed project life of the Prosumer-Approach an annual price inflation factor is introduced.

The economic indicators to compare the BAU-Model with the Prosumer-Model are the "Advantage/Disadvantage vs Grid" results, which are simply the difference between the cost of electricity in the BAU-Approach and the Prosumer-Approach. See "Equation (1)". They can be extracted for each year of the project life and a cumulative sum can be made for the full project life. Additionally, they are calculated as nominal values and as net present values in order to reflect the time value of money.

$$\mathrm{P/L} = \mathrm{BAU\_Cost} - \mathrm{Prosumer\_Cost}$$

where:

P/L = Prosumer-Approach Advantage/Disadvantage vs BAU-Approach in £
BAU_Cost = annual BAU-Approach electricity cost in £
Prosumer_Cost = annual Prosumer-Approach electricity cost in £
Equation (1): Prosumer Advantage/Disadvantage vs Grid

The BAU-Model cost is simply the annual consumption multiplied with the grid electricity cost. See "Equation (2)".

$$\text{BAU\_Cost} = \text{Consumption} * \text{Grid}$$

where:

Consumption = Annual electricity consumption in kWh

Grid = grid electricity price in £/kWh

Equation (2): BAU Electricity Cost

For the Prosumer-Approach various intermediate steps are undertaken to achieve cost transparency. Compare with "Equation (3) to (5)". The LCOE is applied to the electricity consumption at each hierarchy level to ensure that the implied economics in the LCOE calculation are achieved. For the network and administration charges the user has to decide if they are applicable at hierarchy 1 and 2 level or only at level 2. For PV it might be assumed that these charges are only applied at level 2 since such an installation is typically installed on site and never hits the local grid. Whilst a wind installation is more likely to be installed off site and electricity will need to be transported to the consumer. To consider FiT "income" effects the Model applies production credits at each hierarchy level.

$$\text{Prosumer}_{\text{Cost}} = +\text{H}_1\text{\_Cost} + \text{H}_2\text{\_Cost} + \text{H}_3\text{\_Cost}$$

where:

H_n_Cost = hierarchy n electricity cost in £

n = hierarchy level

Equation (3): Prosumer Electricity Cost

$$\text{H}_n\text{\_Cost} = \text{H}_n\text{\_Consumption} * \left(\text{LCOE} + \text{H}_n\text{\_Net} + \text{H}_n\text{\_Admin} - \text{PC}\right)$$

where:

H_n_Consumption = hierarchy n electricity consumption in kWh

LCOE = applicable LCOE in £/kWh

H_n_Net_Charge = applicable hierarchy n network charge in £/kWh

H_n_Admin = applicable hierarchy n administration charge in £/kWh

PC = applicable production credit in £/kWh

n = hierarchy level

Equation (4): Hierarchy 1 and 2 electricity cost

At hierarchy-3 the prosumer has to pay an electricity provider for the provided back-up electricity to balance the system, which is on top of the LCOE. In addition to the production credit they are also credited with the electricity sellback price for the electricity which is sold to the grid. See "Equation (5)".

$$\text{H}_3\text{\_Cost} = \text{H}_3\text{\_Consumption} * \left(\text{LCOE} + \text{BackUp} - \text{Sellback} - \text{PC}\right)$$

where:

H_3_Consumption = hierarchy 3 electricity consumption in kWh

LCOE = applicable LCOE in £/kWh

BackUp = back-up electricity price in £/kWh

Sellback = grid sellback electricity price in £/kWh

PC = applicable production credit in £/kWh

Equation (5): Hierarchy 3 electricity cost

The Model allows for various input parameters, which are mainly load and cost related. Load related parameters were:

- "Annual Production" in kWh, which equals the "Annual Consumption";
- "Hierarchy 1 and 2 Consumption %", which also determines "Hierarchy 3 Consumption %" (equals: 100%—"Hierarchy 1 Consumption %"—"Hierarchy 2 Consumption %");
- "Hierarchy Consumption kWh" at each level as a function of "Annual Consumption" multiplied with "Hierarchy Consumption %" at the respective level; and
- "Sales into Grid" representing excess supply, which cannot be consumed at prosumer pool level and is equal to "Hierarchy 3 Consumption kWh".

Cost/income related inputs included:

- An "Inflation Assumption", which is used to adjust "Production Credits", "Network Charges", "Administration Charges" "Back-up Price Electricity" and "Grid Electricity Prices" over the modeled "Project Life".
- The "Cost-of-Capital" is set at the level of cost-of-capital used in the LCOE calculation and is the basis for the discount factors[1] used to present value the annual economic advantage/disadvantage over the project life.
- "LCOE" without FiT adjustments.
- "Network and Administration Charges", which reflect the potential cost to transport electricity from point of production to point of consumption, e.g. cost for distribution network operator (DNO) line utilization, and to manage and administer the scheme.
- The "Back-up Price Grid Electricity" is the price for grid electricity, which is used at hierarchy-3.
- The "Grid Price Electricity" represents the BAU-Approach energy price.
- The "Production Credits" and "Sellback Price to Grid" can be set to reflect current UK FiT parameters.

The unit of all cost/income parameters is £/kWh apart from the inflation and the cost-of-capital parameters, which are denominated in %.

For each site and technology, a set of simulation results was generated. The following Model input parameters were fixed:

- Annual Production and Consumption = 3902 kWh;
- Inflation = 2.5%,
- Project Life = 20 years;
- Hierarchy-1 Administration and Network charges = 0;
- Hierarchy-2 Administration and Network charges = 3 p/kWh;
- Back-up Price Grid Electricity = 15 p/kWh;
- Sellback Price to Grid = 4.64 p/kWh;
- Grid Price Electricity = 15 p/kWh;
- Production Credit PV = 13.5 p/kWh (UK FiT high rate for 4 - 10 kWp PV as of July 2013 [60]) and wind = 18.4 p/kWh (UK FiT for 100 - 500 kWp as

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[1] Discount factor for year n = 1/(1 + cost-of-capital %)^n.

of July 2013 [61]).

Cost-of-capital, Hierarchy-1 Consumption %, Hierarchy-2 Consumption % and Production Credits were varied. See **Figure 5** for details. The Model calculations based on the above variables resulted in 44,550 and 49,500 simulation results for each wind and PV site respectively, *i.e.* a total of 546,300 data sets.

3. Results

This chapter presents an overview of the Model assumptions, summary results, site-specific results and the sensitivity analysis based on LCOE break-even calculation.

3.1. Overview of Model Summary Results

The term P/L (profit/loss) will be used interchangeably for the "Advantage/Disadvantage vs. Grid" results, whilst a positive P/L indicates an advantage for the Prosumer-Approach (hence a disadvantage for the BAU-Approach). An overview of the summary results can be found in **Tables 2-4**.

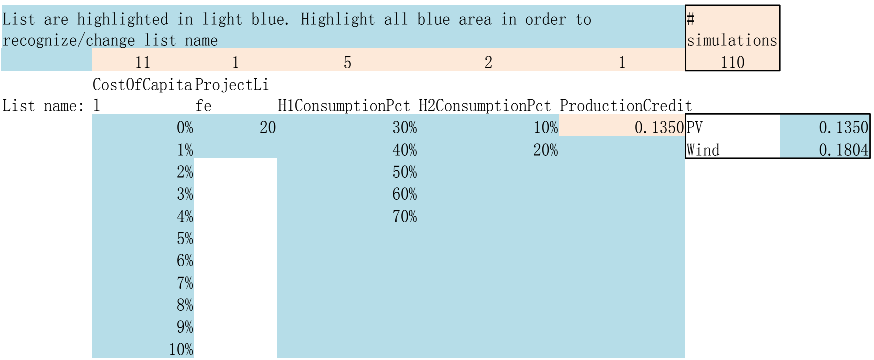
Table 2 and **Table 3** show for each site and technology the minimum and maximum "Advantage/Disadvantage vs. Grid" Model results. These results have been normalized for 1000 kWh/yr consumption.

The lowest PV P/Ls coincided with highest LCOE, which had the following parameter settings:

- lowest modeled irradiation value,
- maximum capital multiplier,
- 20 years panel life,
- West orientation,
- cost-of-capital of 10%,
- hierarchy-1 consumption of 30% and
- hierarchy-2 consumption of 10%.

The highest PV P/Ls coincided with lowest LCOE, which had the following parameter settings:

- highest modeled irradiation value,
- minimum capital multiplier,



List are highlighted in light blue. Highlight all blue area in order to recognize/change list name						# simulations	
	11	1	5	2	1	110	
List name:	CostOfCapital	ProjectLife	H1ConsumptionPct	H2ConsumptionPct	ProductionCredit		
	0%	20	30%	10%	0.1350	PV	0.1350
	1%		40%	20%		Wind	0.1804
	2%		50%				
	3%		60%				
	4%		70%				
	5%						
	6%						
	7%						
	8%						
	9%						
	10%						

Figure 5. Simulated Model parameters.

Table 2. PV summary Model results. The table shows how better/worse a prosumer scenario compares to a BAU scenario based on a one year and project lifetime horizon. Only minimum and maximum values are displayed defining the result range. These values coincided with the best and worst-case Model settings. Sites are ordered by increasing irradiation level (IV1 lowest and TR14 highest) and geographic identifiers can be found in Table 1.

PV Identifier	LCOE £/kWh	Advantage/Disadvantage yr 1 £/1000 kWh/yr	Advantage/Disadvantage Project Life £/1000 kWh/yr	
PV generic IV1	0.580	−£363.16	−£2783.00	Min
PV generic IV1	0.132	£130.64	£4507.61	Max
PV generic CA2	0.569	−£352.16	−£2687.87	Min
PV generic CA2	0.134	£128.64	£4465.61	Max
PV generic YO24	0.530	−£313.16	−£2350.57	Min
PV generic YO24	0.115	£147.64	£4864.61	Max
PV generic KT2	0.491	−£274.16	−£2013.27	Min
PV generic KT2	0.118	£144.64	£4801.61	Max
PV generic SY23	0.448	−£231.16	−£1641.38	Min
PV generic SY23	0.106	£156.64	£5053.61	Max
PV generic TR14	0.432	−£215.16	−£1503.00	Min
PV generic TR14	0.105	£157.64	£5074.61	Max

Table 3. Wind summary Model results. The table shows how better/worse a prosumer scenario compares to a BAU scenario based on a one year and project lifetime horizon. Only minimum and maximum values are displayed defining the result range. These values coincided with the best and worst-case Model settings. Sites are ordered by increasing average wind speed (KT2 lowest and TR14 highest) and geographic identifiers can be found in Table 1.

Wind Identifier	LCOE £/kWh	Advantage/Disadvantage yr 1 £/1000 kWh/yr	Advantage/Disadvantage Project Life £/1000 kWh/yr	
Enercon 33 45 m KT2	0.215	£47.24	£852.38	Min
Enercon 33 45 m KT2	0.031	£277.04	£7892.44	Max
Enercon 33 45 m YO24	0.206	£56.24	£930.22	Min
Enercon 33 45 m YO24	0.030	£278.04	£7913.44	Max
Enercon 33 45 m CA2	0.188	£74.24	£1085.90	Min
Enercon 33 45 m CA2	0.028	£280.04	£7955.45	Max
Enercon 33 45 m IV1	0.178	£84.24	£1172.38	Min
Enercon 33 45 m IV1	0.027	£281.04	£7976.45	Max
Enercon 33 45 m SY23	0.154	£108.24	£1379.95	Min
Enercon 33 45 m SY23	0.024	£284.04	£8039.45	Max
Enercon 33 45 m TR14	0.130	£132.24	£1587.52	Min
Enercon 33 45 m TR14	0.021	£287.04	£8102.44	Max

Table 4. Input parameter and Model result sensitivity matrix. It shows what effect a parameter change has on the P/L, e.g. if LCOE goes up the P/L will go down.

	LCOE	Production Credit	Inflation assumption	Cost of Capital	Hierachy 1 consumption %	Hierachy 2 consumption %	Hierachy 3 consumption %
Parameter	up	up	up	up	up	up	up
P/L	down	up	up	down	up	up	down
	Hierachy 1 Network Charge	Hierachy 2 Network Charge	Hierachy 1 Admin Charge	Hierachy 2 Admin Charge	Back up Price Grid Electricity	Sellback Price to Grid	Grid Price Electricity
Parameter	up	up	up	up	up	up	up
P/L	down	down	down	down	down	up	up

- 25 years panel life,
- South orientation,
- cost-of-capital of 0%,
- hierarchy-1 consumption of 70% and
- hierarchy-2 consumption of 20%.

For wind the same P/L pattern results were observable and the same and parameter settings were used apart from lowest/highest wind speed and 15/25 yrs turbine life.

Table 4 shows the general sensitivity of the P/L to changes of the input parameters. Generally, the lower the LCOE was, the higher was the "Advantage/Disadvantage vs. Grid". The same was true for cost-of-capital, back-up electricity price and network and administration charges. The higher inflation, hierarchy 1 and 2 consumption, sellback price to the grid and grid electricity prices was the higher was the P/L. Although the LCOE is the most important parameter its impact can be overwritten by changes to any of the other parameter or their cumulative effects. However, for the same LCOE different P/L results were plausible and recorded. All sites showed the same patterns for the various parameter combinations although the sites with the best natural resources would have the lowest LCOE and hence the highest recorded P/L and vice versa for the sites with the highest LCOE. See Table 2 and Table 3. Wind showed more homogenous results on a relative basis and lower LCOE also indicate a stabilizing effect on the P/L indicator. The following differences between best and worst site for the lowest and highest LCOE were recorded (discounted lifetime P/L per 1000 kWh/yr consumption):

- lowest LCOE Wind: TR14 £8102.44 vs KT2 £7892.44, difference £210.00.
- lowest LCOE PV: TR14 £5074.61 vs CA2 £4465.61, difference £609.00.
- highest LCOE Wind: TR14 £1587.52 vs KT2 £852.44, difference £735.14.
- highest LCOE PV: TR14 £−1503.00 vs IV1 £−2783.00, difference £1280.00.

3.2. Site Specific Model Results

For all six sites, load class type and technology, a further analysis step based on anchor RE cover ratios was undertaken. These were derived from the self-consumption levels calculated in the Authors earlier paper [1]. For each observed LCOE the average simulated "Advantage/Disadvantage vs Grid" (P/L) was calculated whilst different P/Ls for one and the same LCOE were quite common. The used anchor RE cover ratios were rounded to the nearest 10% and the following combinations were used. For wind and load class-1 (domestic) and class-3 (commercial) the hierarchy-1 consumption was set at 50% and hierarchy-2 consumption was set at 10%. (Apart from site TR14 were 50% and 20% respectively was used since simulation indicated a higher achievable hierarchy-2 consumption). For all PV sites and load class-1 a hierarchy-1 consumption of 30% and hierarchy-2 consumption of 10% was analyzed and for load class-3 it was 40% and 10% respectively. Around 5,000 data points for each scenario were filtered and graphed against P/L, LCOE and cost-of-capital. See **Figure 6** and **Figure 7**.

3.2.1. Site Specific wind Model Results

Every scenario showed positive P/L for all sites. The sites with the best wind resource also had the tightest LCOE and P/L range. See **Table 5**. The sample graph of **Figure 6** also demonstrates how cost-of-capital influences the LCOE and P/L. All the low LCOE coincide with low cost-of-capital and high average P/L values and vice versa. The three-dimensional graphs show a sliding corridor where the slope is from the highest to the lowest P/L value and the width is defined by a LCOE range. However, that LCOE range (corridor width) is making incremental shifts to a higher LCOE boundary with an increasing cost-of-capital. For the different hierarchy-1 and -2 consumption scenarios the same pattern could be

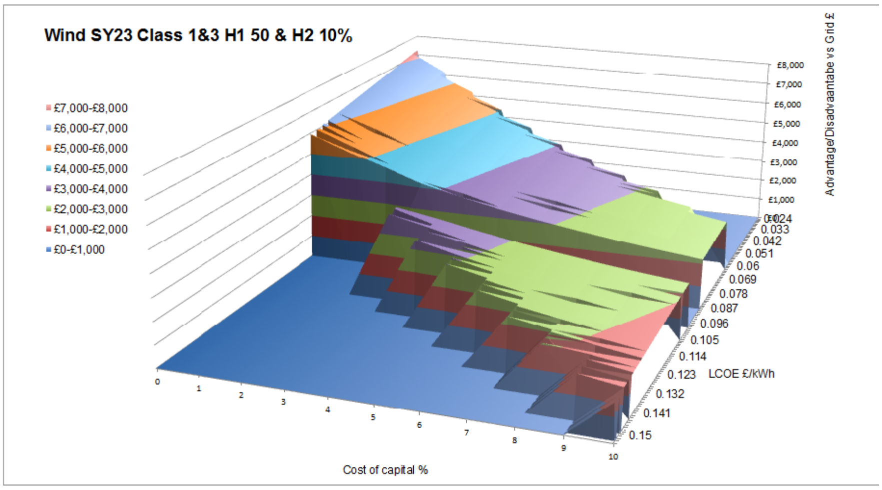


Figure 6. SY23 site-specific average wind "Advantage/Disadvantage vs Grid" per LCOE and cost-of-capital. Load class-1 & class 3, hierarchy-1 consumption 50% and hierarchy-1 consumption 10%. Sliding corridor demonstrate which P/L value range coincides with respective LCOE and cost-of-capital parameters. High P/L values correlate with low LCOE and low cost-of-capital. For the different hierarchy-1 and -2 consumption scenarios the same pattern could be observed, although the average P/L values shifted upwards with higher hierarchy-1 and -2 consumption values. The other sites showed the same pattern.

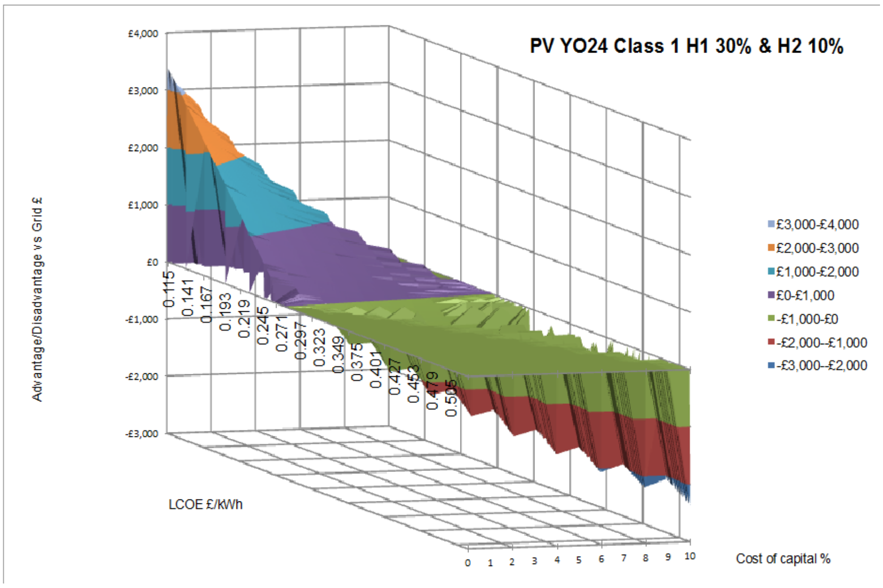


Figure 7. YO24 site-specific average PV "Advantage/Disadvantage vs Grid" per LCOE and cost-of-capital. Load class-1, hierarchy-1 consumption 30% and hierarchy-2 consumption 10%. Sliding corridor demonstrate which P/L value range coincides with respective LCOE and cost-of-capital parameters. High P/L values correlate with low LCOE and low cost-of-capital. The other sites showed the same pattern.

Table 5. Wind site specific lowest/highest average "Advantage/Disadvantage vs Grid". Hierarchy-1 consumption was set at 50% and hierarchy-2 consumption was set at 10% apart from TR14 where it was set at 20%. Sites are ordered by increasing average wind speed (KT2 lowest and TR14 highest).

Wind	Load Class 1 & 3			
Site	LCOE range £/kWh	lowest avg P/L at 10% cost of capital	highest avg P/L at 0% cost of capital	highest minus lowest
KT2	0.031 - 0.210	£1088.00	£7099.00	£6011.00
YO24	0.030 - 0.206	£1166.00	£7120.00	£5954.00
CA2	0.028 - 0.188	£1322.00	£7162.00	£5840.00
IV1	0.027 - 0.178	£1408.00	£7183.00	£5775.00
SY23	0.024 - 0.154	£1616.00	£7246.00	£5630.00
TR14	0.021 - 0.130	£1878.00	£7462.00	£5584.00

observed, although the average P/L values shifted upwards with higher hierarchy-1 and -2 consumption values.

3.2.2. Site Specific PV Model Results

The PV sites recorded a wide range of positive to negative P/Ls. A better solar resource also coincided with a tighter LCOE and P/L range. The P/L swing between wind and PV was similar, although the LCOE for PV were significantly higher. See Table 6. The sample graph of Figure 7 for load class-1 (hierarchy-1 30% and hierarchy-2 10%) show a similar sliding corridor pattern and dynamics as for wind, which was also observable PV/load class-3 scenarios (hierarchy-1

Table 6. PV site-specific lowest/highest average "Advantage/Disadvantage vs Grid". Hierarchy-1 consumption was set at 30% and 40% for load class-1 (domestic) and class-3 (non-domestic) respectively and hierarchy-2 consumption was set at 10%. Sites are ordered by increasing average solar irradiation levels (IV1 lowest and TR14 highest).

PV	Load Class 1			
Site	LCOE range £/kWh	lowest avg P/L at 10% cost of capital	highest avg P/L at 0% cost of capital	highest minus lowest
IV1	0.132 - 0.580	−£2783.00	£3074.00	£5857.00
CA2	0.134 - 0.569	−£2688.00	£3032.00	£5720.00
YO24	0.115 - 0.530	−£2351.00	£3431.00	£5782.00
KT2	0.118 - 0.491	−£2013.00	£3368.00	£5381.00
SY23	0.106 - 0.448	−£1641.00	£3620.00	£5261.00
TR14	0.105 - 0.432	−£1503.00	£3641.00	£5144.00
PV	Load Class 3			
IV1	0.132 - 0.580	−£2665.00	£3394.00	£6059.00
CA2	0.134 - 0.569	−£2570.00	£3352.00	£5922.00
YO24	0.115 - 0.530	−£2233.00	£3751.00	£5984.00
KT2	0.118 - 0.491	−£1895.00	£3688.00	£5583.00
SY23	0.106 - 0.448	−£1523.00	£3940.00	£5463.00
TR14	0.105 - 0.432	−£1385.00	£3961.00	£5346.00

40% and hierarchy-2 10% setting). Still, the P/L turns negative at a break-even point. These points are presented in Table 7. The break-even points were reached at similar levels for the different sites, however, not necessarily at the same cost-of-capital highlighting the impact of other input parameters.

3.3. LCOE Break-Even Calculation

In order to assess the impact of single parameters on the economic viability of projects, LCOE break-even calculations have been performed and the results are shown below. The LCOE break-even represents the point where the Prosumer-Approach and BAU-Approach are considered economically neutral and where the discounted project-lifetime P/L is zero. The higher the LCOE break even the higher is the chance that the RE installation is economical and competitive against conventional electricity. The following default settings have been used to perform the analysis:

- Annual Production and Annual Consumption = 1000 kWh
- Hierarchy 1 Consumption: 40%
- Hierarchy 2 Consumption: 10%
- Inflation: 2.5%
- Cost-of-capital: 5%
- Project Life: 20 years
- Production Credit: 0.135 £/kWh (UK FiT high rate for 4 - 10 kWp PV as of

Table 7. PV break-even points for "Advantage/Disadvantage vs Grid" for site-specific Model results.

Site	Low LCOE break-even in £/kWh	at cost of capital of	High LCOE break-even in £/kWh	at cost of capital of
PV – P/L break-even – Load Class-1				
IV1	£0.262	10%	£0.279	0%
CA2	£0.261	10%	£0.279	0%
YO24	£0.259	10%	£0.277	1%
KT2	£0.259	10%	£0.274	2%
SY23	£0.259	10%	£0.272	3%
TR14	£0.261	10%	£0.270	3%
PV – P/L break-even – Load Class-3				
IV1	£0.276	8%	£0.293	1%
CA2	£0.276	8%	£0.289	2%
YO24	£0.272	10%	£0.289	2%
KT2	£0.272	10%	£0.287	3%
SY23	£0.272	10%	£0.285	4%
TR14	£0.272	10%	£0.291	4%

July 2013 [60])

- Sellback Price to Grid: 0.0464 £/kWh (UK export tariff as of July 2013 [61])
- Hierarchy 1 Network and Administration Charge: 0.00 £/kWh
- Hierarchy 2 Network and Administration Charge: 0.03 £/kWh
- Back-up Price Electricity and Grid Electricity Price: 0.15 £/kWh

Based on these input parameters and a zero project-lifetime P/L a LCOE break-even of 0.282 £/kWh was calculated. This value will be used as benchmark to assess further simulation results.

3.3.1. LCOE Break-Even Analysis—Hierarchy 1 & 2 Consumption

Hierarchy-1 consumption % has been modified in 10% steps from 30% - 70% and hierarchy-2 consumption % has been modified in 5% steps from 0% - 20%. Summary results can be found in **Table 8** and **Figure 8**.

The LCOE break-even difference between lowest and highest simulated consumption percentage was ca. 0.05 £/kWh and ca. 0.01 £/kWh for hierarchy-1 consumption % and hierarchy-2 consumption % respectively. The higher the hierarchy-1 and -2 consumption % inputs were the higher was the LCOE break-even. In comparison to the LCOE benchmark the best consumption scenario moved the LCOE break-even by around 18% up whilst in the worst scenario the LCOE break-even was only 7.5% lower.

3.3.2. LCOE Break-Even Analysis—Inflation and Cost-of-Capital

Inflation has been varied in 1% steps from 0% - 4% and cost-of-capital has been varied in 1% steps from 0% - 10%. Summary results can be found in **Table 9** and

Table 8. LCOE break-even analysis—hierarchy 1 & 2 consumption results table. Comparison of Min/Max table values against benchmark LCOE break-even point. Min/Max values are highlighted in green and benchmark break-even value is highlighted in orange.

		Hierachy 1 consumption %				
Hierachy 2 consumption %		30%	40%	50%	60%	70.0%
	0%	0.261	0.275	0.289	0.304	0.318
	5%	0.264	0.279	0.293	0.307	0.322
	10%	0.268	0.282	0.296	0.311	0.325
	15%	0.271	0.285	0.300	0.314	0.328
	20%	0.274	0.289	0.303	0.317	0.332
				delta £/kWh	delta %	
	Benchmark break-even		0.282	−0.021	−7.5%	Min
				0.050	17.7%	Max

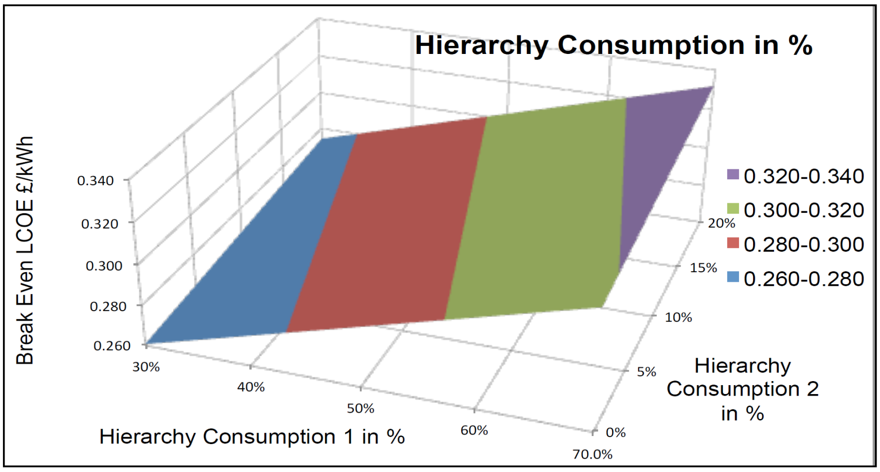


Figure 8. LCOE break-even analysis—hierarchy 1 & 2 consumption results graph.

Table 9. LCOE break-even analysis—inflation and cost-of-capital results table. Comparison of Min/Max table values against benchmark LCOE break-even point. Min/Max values are highlighted in green and benchmark break-even value is highlighted in orange.

	Cost of Capital										
Inflation	0.0%	1.0%	2.0%	3.0%	4.0%	5.0%	6.0%	7.0%	8.0%	9.0%	10.0%
0%	0.227	0.227	0.227	0.227	0.227	0.227	0.227	0.227	0.227	0.227	0.227
1%	0.251	0.250	0.249	0.249	0.248	0.247	0.246	0.246	0.245	0.244	0.244
2%	0.278	0.277	0.275	0.273	0.271	0.270	0.268	0.266	0.265	0.263	0.262
3%	0.310	0.307	0.304	0.301	0.298	0.295	0.292	0.290	0.287	0.285	0.282
4%	0.346	0.341	0.337	0.332	0.328	0.324	0.320	0.316	0.312	0.309	0.305
				delta £/kWh	delta %						
Benchmark break-even			0.282	−0.055	−19.4%	Min					
				0.064	22.7%	Max					

Figure 9.

The inflation impact on the LCOE break-even was up to 0.12 £/kWh at 0% cost-of-capital. At higher cost-of-capital that effect is less pronounced. The Cost-of-capital impact over the simulated range was a maximum of 0.04 £/kWh (assuming same inflation) representing a modest relative increase from lowest and highest recorded LCOE break-even of around 13%. Compared to the benchmark LCOE the simulated break-even value varied in a ca. +/- 20% corridor.

3.3.3. LCOE Break-Even Analysis—Network and Administration Charges

Network and administration charges at hierarchy-1 and -2 have been simulated as pairs in 0.02 £/kWh steps from 0.00 to 0.08£/kWh for each charge. Summary results can be found in Table 10 and Figure 10.

Any network and administration charge pair in isolation impacts on the LCOE break-even by 0.02 £/kWh and 0.08 £/kWh for hierarchy-2 and hierarchy-1 charges respectively. If both pairs are stressed to the maximum simulated value than the difference is 0.10 £/kWh, which then represents a percentage

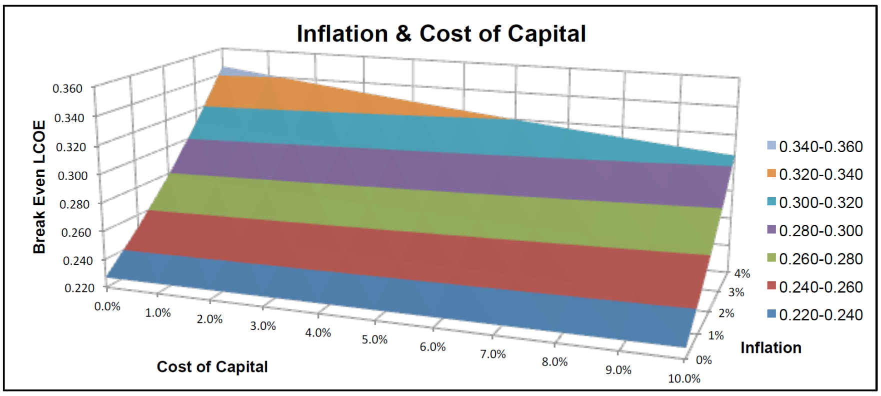


Figure 9. LCOE break-even analysis—inflation and cost-of-capital results graph.

Table 10. LCOE break-even analysis—network and administration results table. Comparison of Min/Max table values against benchmark LCOE break-even point. Min/Max values are highlighted in green and benchmark break-even value is highlighted in orange.

		H1 Network & Admin Charge £/kWh				
H2 Network & Admin Charge		0.00	0.02	0.04	0.06	0.08
£/kWh	0.00	0.290	0.269	0.249	0.229	0.208
	0.02	0.284	0.264	0.244	0.224	0.203
	0.04	0.279	0.259	0.239	0.219	0.198
	0.06	0.274	0.254	0.234	0.213	0.193
	0.08	0.269	0.249	0.229	0.208	0.188
				delta £/kWh	delta %	
	Benchmark break-even		0.282	−0.094	−33.3%	Min
				0.008	2.7%	Max

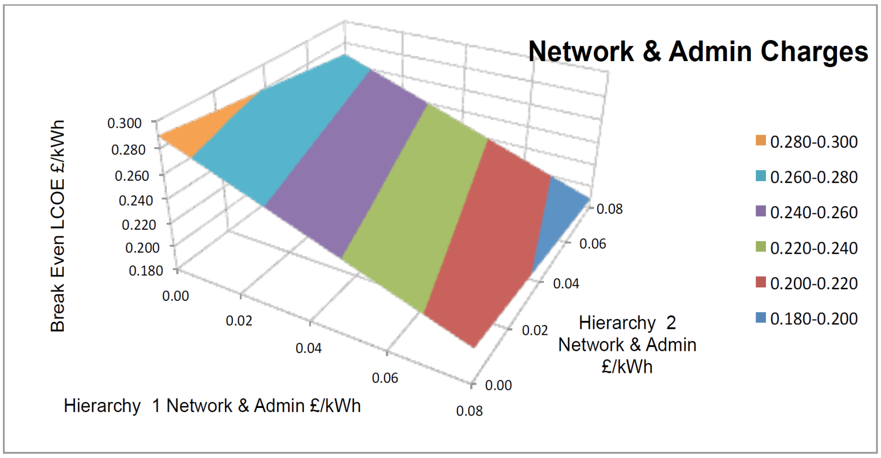


Figure 10. LCOE break-even analysis—network and administration results graph.

difference of over 50% compared to the lowest LCOE break-even. Versus the benchmark point the break-even values change by plus ca. 3% for zero charges and ca. −33% for very high charges of 8p for network and administration each at both hierarchy levels.

3.3.4. LCOE Break-Even Analysis—Back-up Electricity Price, Grid Sellback Price and Grid Electricity Price

The back-up, grid sellback and grid electricity price have been modeled in 0.05 £/kWh steps in ranges from 0.15 to 0.35 £/kWh, 0.00 to 0.20 £/kWh and 0.15 to 0.35 £/kWh respectively. Summary results are presented in Table 11 and Figure 11.

Back-up electricity prices stressed in isolation had an impact on the LCOE break-even range of ca. 0.13 £/kWh with a higher back-up electricity price causing the LCOE break-even to go down. Sellback to grid price variations had the reverse impact on the LCOE break-even price level with a 0.20 £/kWh change impacting the LCOE break-even by around 0.10 £/kWh. Higher grid electricity prices caused up to 0.25 £/kWh higher LCOE break-even prices. However, calculated combinations where grid electricity price is higher than the back-up electricity price can be considered unlikely and are hence shaded in the table.

3.3.5. LCOE Break-Even Analysis—Production Credit and Grid Electricity Price

The production credits and grid electricity prices have been modeled in 0.05 £/kWh steps in ranges from 0.00 to 0.15 £/kWh and 0.15 to 0.35 £/kWh respectively. In the analysis the back-up electricity price was also always at the same level as the grid electricity price. Summary results are presented in Table 12 and Figure 12.

A production credit difference of 0.15 £/kWh has an impact on the LCOE break-even of ca. 0.19 £/kWh. The range around the benchmark value was −60% to 50%. The analysis shows that higher grid price have a strong impact on LCOE break-even and can be a catalyst for lower production credits.

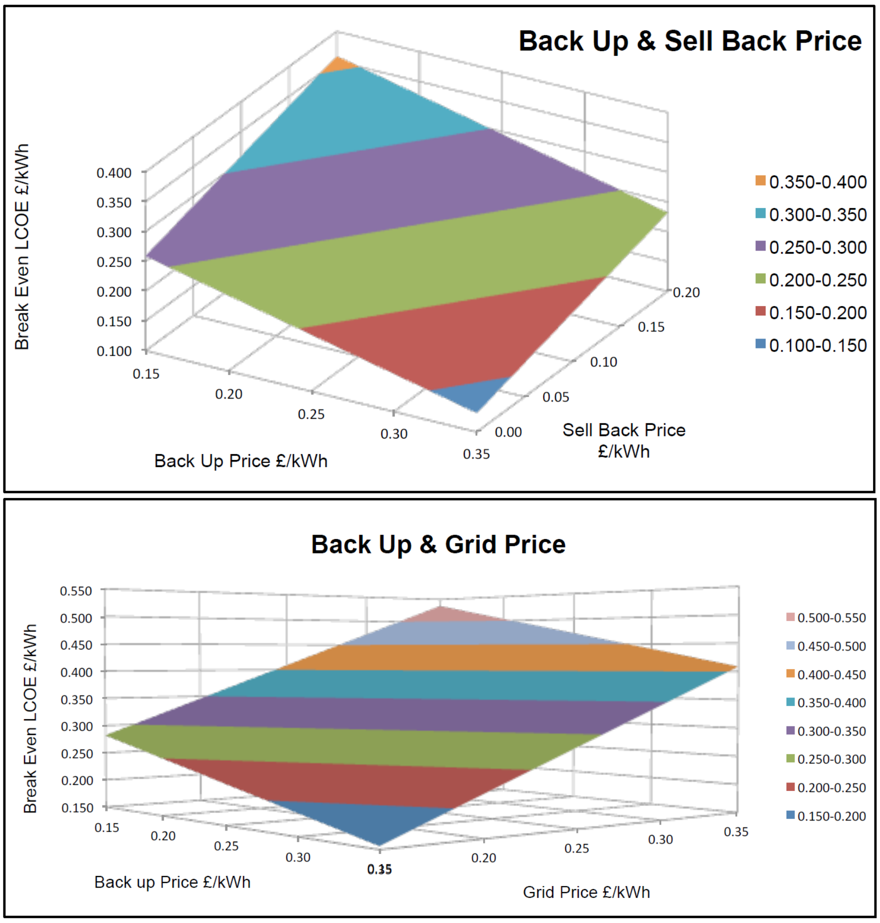


Figure 11. LCOE break-even analysis—back-up price, grid sellback price and grid electricity price results graph.

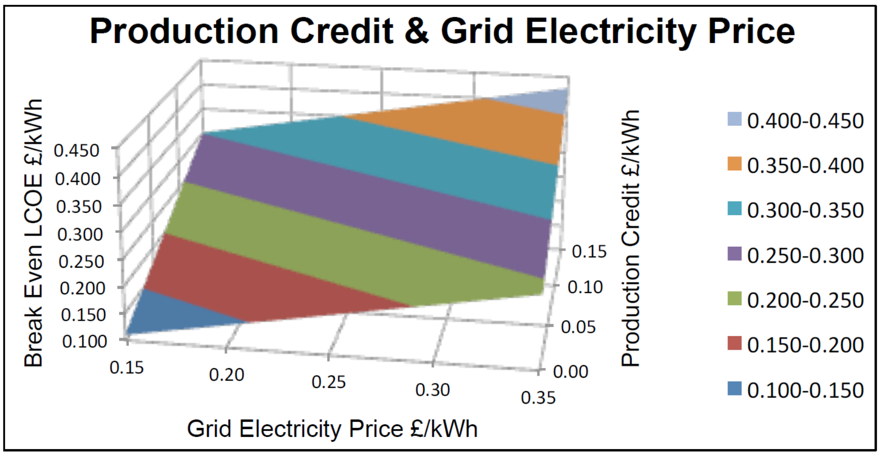


Figure 12. LCOE break-even analysis—production credit and grid electricity price results graph.

4. Discussion of Model Results

The Model results suggest that a Prosumer-Approach can have its economic merits and offer benefits to single consumers and communities. All analyzed sites

Table 11. LCOE break-even analysis—back-up electricity price, grid sellback price and grid electricity price results table. Comparison of Min/Max table values against benchmark LCOE break-even point. Min/Max values are highlighted in green and benchmark break-even value is highlighted in orange.

		Back up Price £/kWh				
Sellback Price		0.15	0.20	0.25	0.30	0.35
£/kWh	0.00	0.259	0.227	0.195	0.164	0.132
	0.05	0.284	0.252	0.220	0.189	0.157
	0.10	0.309	0.277	0.245	0.214	0.182
	0.15	0.334	0.302	0.270	0.239	0.207
	0.20	0.359	0.327	0.295	0.264	0.232
				delta £/kWh	delta %	
	Benchmark break-even		0.282	−0.150	−53.2%	Min
				0.077	27.2%	Max

			Back up Price £/kWh			
Grid Price £/kWh		0.15	0.20	0.25	0.30	0.35
	0.15	0.282	0.250	0.218	0.187	0.155
	0.20	0.345	0.314	0.282	0.250	0.218
	0.25	0.409	0.377	0.345	0.314	0.282
	0.30	0.472	0.440	0.409	0.377	0.345
	0.35	0.536	0.504	0.472	0.440	0.409
				delta £/kWh	delta %	
	Benchmark break-even		0.282	−0.127	−45.0%	Min
				0.254	90.0%	Max

and technologies indicated the economic attractiveness of the Prosumer-Model under specific assumptions. Yet, there is not a straight linear pattern since the final economics are dependent on a whole set of factors, which can either neutralize or amplify each other.

The LCOE is a major input factor into the Model and it is dependent on various assumptions. The LCOE of PV and wind is characterized by little expected volatility, which protects prosumers from rising energy prices but also excludes them from the benefits of falling prices. However, in the BAU-Approach the grid electricity price is the dominant factor when considering energy consumption as relatively stable.

The LCOE break-even analysis was designed to isolate Model inputs, vary them and quantify their impact on the LCOE break-even. In order to rank their impact the p/kWh difference of the simulated min/max values has been taken into account and can be seen in brackets. The least relevant parameters in the simulations were hierarchy-2 consumption (1 p/kWh), hierarchy-2 network &

Table 12. LCOE break-even analysis—production credit and grid electricity price results table. Comparison of Min/Max table values against benchmark LCOE break-even point. Min/Max values are highlighted in green and benchmark break-even value is highlighted in orange.

	Production Credit £/kWh				
Grid Price £/kWh	0.00	0.05	0.10	0.15	
0.15	0.111	0.174	0.238	0.301	
0.20	0.142	0.206	0.269	0.333	
0.25	0.174	0.238	0.301	0.364	
0.30	0.206	0.269	0.333	0.396	
0.35	0.238	0.301	0.364	0.428	
			delta £/kWh	delta %	
Benchmark break-even		0.282	−0.171	−60.7%	Min
			0.146	51.7%	Max

administration charges (2 p/kWh), cost-of-capital (4 p/kWh) and hierarchy-1 consumption (5 p/kWh). A moderate impact was observed for hierarchy-1 network & administration charges (8 p/kWh), sellback electricity prices (10 p/kWh), inflation (12 p/kWh) and back-up electricity prices (13 p/kWh). The highest impact could be observed in production credits (19 p/kWh) and the grid electricity price (25 p/kWh).

Grid electricity prices had a significant impact on the Model results. That can be explained by the fact that it is an essential part of the BAU-Approach calculation and that it is inflation-linked, *i.e.* these costs can only be stable or go up in the Model settings. A change of the grid electricity price is also likely to correlate positively with back-up electricity prices and sellback to grid prices.

Production credit has been the next biggest effect on the LCOE break-even. The modeled production credit level has been relatively substantial, almost the same as the simulated back-up electricity price, and both were inflation-linked. This means that over time an increasingly positive effect on the Prosumer-Approach calculation results is observable in high inflation scenarios. However, when considering modeled RE LCOE levels and assuming continuing trends for lower RE equipment prices and higher electricity prices then even scenarios with no production credits are economically plausible and attractive.

The back-up electricity prices impact is less pronounced since the used back-up electricity is a function of the hierarchy-3 demand to balance any remaining electricity need. The impact can actively be reduced with increasing hierarchy-1 & 2 consumption levels. Back-up electricity had been modeled inflation-linked, which amplifies this effect since the LCOE is fixed. This also ties in with results from Energiewende and DSM research, which showed that consumers do adjust consumption behavior to price signals [22] [46] [62] [63] [64]. The reverse is true for sellback prices into the grid, *i.e.* the higher hierarchy-3 levels, the higher the impact of sellback prices on the P/L.

The impact of inflation is based on its links to the various input parameters and the compounding effects. In the BAU-Approach increasing inflation always has an increasing effect on P/L. However, in the Prosumer-Approach inflation affects different variables that partially offset each other.

Cost-of-capital had very little impact in the Model simulation itself, because it was only used to discount the difference between BAU-Approach and Prosumer-Approach. Still, it should be noted that the cost-of-capital is one of the most important factors in the LCOE calculation feeding into the model [1].

Network and administration charges on their own have limited influence on Model results. Nonetheless, it is probably realistic to assume they could move in parallel for both hierarchy levels, hence they start becoming more meaningful, e.g. for wind. The hierarchy-1 & 2 consumption parameters seemed to have relatively little impact at current electricity price levels.

All Model assumptions are static, e.g. they assume constant energy supply and demand over time, or follow a trend, e.g. a constant inflation number. Although static assumptions were useful for the modeling process they are not realistic. In real life scenarios prosumer needs and behavior might change, inflation of various costs will not be uniform and natural resources will fluctuate. Moreover, technical problems or advances could influence the supply level of electricity. The hierarchal structure and mix of technologies and installations in the pool should be able to smooth some of these effects. However, on an individual level fluctuations of these factors would imply P/L swings and therefore compromise the simulation results.

5. Conclusions

Overall it can be concluded that a Prosumer-Approach could offer significant economic opportunities to the UK. Based on the current conditions such an energy model could bring economic advantages to consumers, yet by doing so it would necessitate/cause changes to market structures over time. The UK electricity market is shaped by a highly concentrated market structure. Its infrastructure is based on a centralized energy generation and a bias towards a top-down electricity distribution system. A prosumer system is by design decentralized and more democratic. Hence, the widespread adoption of such a system would impact almost all elements of the market over time. That could mean that society and communities might see more direct involvement with electricity markets and on different levels. Regulation and market rules would need to be adapted to ensure consumer protection, competition, energy security and grid access. Economically, it would open the market for new business models and technologies, with the aim to abolish the necessity for FiT as they are known today. The opportunity would be to reduce the dependency on volatile fossil fuel based energy markets. It could also be a catalyst to develop new funding sources for the modernization of the generation infrastructure and the implementation of ICT as means to increase efficiency in the electricity market. Technically a gradual adoption to a bi-directional grid and the co-ordination of changing generation and consumption profiles would be required. All the above would be a gradual or partial process with the need to balance conflicting interest.

The Model simulation demonstrated that a Prosumer-Model could bring economic advantages to prosumers across the UK. For wind scenarios an economic advantage of the prosumer approach vs the BAU approach of £47 to £287 per 1000 kWh/yr consumption was calculated. Whilst for PV scenarios the comparison was less favorable with showing a range of £−363 to £158 per 1000 kWh/yr consumption. However, the results are heavily dependent on assumptions and future cost developments. The Model worked with a total of 15 input parameters, which partly neutralize or amplify each other. Some could be considered correlated and that introduced a considerable uncertainty and complexity to the Model results. The LCOE break-even analysis provided some indication, to which parameters the Model results were particularly sensitive to. In this context specifically, the electricity price parameters used were of significant importance and the production credits available via the FiT as well. In a high grid price scenario of 0.35 £/kWh the break-even price was modeled at 0.43 £/kWh vs the benchmark break-even of 0.28 £/kWh whilst in a zero production credit scenario the break-even price was modeled at 0.11 £/kWh. Through its compounding effects and the effects of the starting value, inflation can amplify these effects even further. Although the cost-of-capital element has a limited direct effect on the Model results it was a very influential factor to the LCOE Prosumer-Model input as demonstrated in earlier paper of the Authors [1]. It is also a factor, which is mostly self-determined by the prosumer, although not completely independent of general interest rates and other investment yields. The different cross-dependencies of input and model dynamics make the results very assumption dependent and offer opportunities for further research.

Correlations of individual parameters have not been considered separately and it would be feasible to extend future analysis to incorporate this. Specifically cost-of-capital and inflation; the relationship between the electricity price parameters, equipment cost (as factor of the LCOE calculation) and production credits; as well as hierarchy-1 consumption and grid electricity prices in the context of grid parity and DSM could provide further interesting results.

The presented P/L results focused on the project lifetime advantage/disadvantage of the simulated scenarios. Yet, it has been quite a common observation that projects were having a negative P/L in the early years, with positive P/L in the later years compensating for this. This delayed harvesting of benefits of an investment could be seen as a negative point in a decision making process, since it increases the dependency on the underlying assumptions and hence the uncertainty of the expected results.

The paper has been focusing on the quantitative Model results. However, there are also qualitative aspects of the Prosumer-Model, which are worth highlighting in the wider UK market context. Qualitative aspects of the Model results may be relating to sociological, economic, technological and regulatory issues and opportunities that need to be considered. From a social aspect the behavior changes towards energy generation and consumption are unpredictable. A prosumer system, as proposed by this research, might help balancing out some of these aspects by increasing transparency, influencing demand behavior and boosting community acceptance of electricity infrastructure investments. Economically it might be an opportunity to mobilize private investment into the energy infrastructure, stabilize energy prices and thus stimulate the economy across the UK over the years. Technologically the design and management of the supporting grid infrastructure is very important and the mix of RE technologies might even help to improve system stability and economics even if it seems disadvantageous for the individual. Regulatory decisions will influence all aspects of the electricity market and without their consideration a widespread implementation of a prosumer system is very unlikely.

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