Unlocking the Economic Viability of Marginal UKCS Discoveries: Optimising Cluster Developments

*Dr Yakubu Abdul-Salam[1]; Prof Alex Kemp[1]; Prof Euan Phimister[1,2]

*Corresponding author: y.abdul-salam@abdn.ac.uk; University of Aberdeen, Business School Office, S36 Edward Wright Building, Dunbar Street, Old Aberdeen, AB24 3QY, Scotland, UK
[1] Aberdeen Centre for Research in Energy Economics and Finance, University of Aberdeen
[2] Business School, University of Stellenbosch, South Africa

Abstract

Hundreds of newly discovered or previously appraised but undeveloped UKCS fields are small. As standalone developments, many of these fields are economically unviable. Meanwhile to extend the term of exploration and production activities in the mature UKCS province, the UK government and allied institutions have renewed focus on maximising economic recovery (MER). To this end, a significant aspect of the strategy should be to unlock the potential of small, undeveloped and economically marginal UKCS fields. From the standpoint of operators, clustering these fields into unit developments with shared communal infrastructure is an innovative way of reducing development and operating expenditures through economies of scale, hence enhancing their economic viability. We develop a detailed mathematical optimisation model to examine the potential of cluster developments in unlocking the economic viability of marginal UKCS fields. We find that relative to standalone developments, cluster developments offer a unique opportunity to unlock the economic potential of many of these fields. At the existing levels of costs, prices and taxation, cluster developments facilitate the unlocking of up to 8.70 times the value from standalone developments in post-tax net present value (NPV) terms, with about $18.05 billion in total NPV to be unlocked across the UKCS province. This is higher in pre-tax NPV terms, with cluster developments facilitating the unlocking of up to $36.97 billion across the province, compared to only $7.76 billion for standalone developments. Further analysis show that the economics of the marginal fields exhibit significant sensitivity to market oil and gas prices. However, in terms of actions that are in investors' direct control, use of clustering as a cost reduction strategy would likely make the most significant difference if the MER goal in the UKCS province is to be realised.

Keywords: Clusters; Marginal; Optimisation; Economies of Scale; MER; UKCS

1 Introduction

Oil and gas exploration and production activities have been successfully undertaken in the UK Continental Shelf (UKCS) since the 1960s. The UKCS is currently considered a mature province. Many of the newly discovered or previously appraised but undeveloped fields are small, with the great majority of these having potential reserves of less than twenty million barrels of oil equivalent. As standalone developments, several of these fields are economically unviable to the extent that some of them have been relinquished by the licensees who originally discovered them. At the same time production in many UKCS operated fields is exhausted, with much imminent cessation of production and decommissioning planned over the coming decade.

It is against this background that the UK government and allied institutions including the Oil and Gas Authority (OGA), which is the industry regulatory body, have renewed focus on maximising economic recovery (MER) from oil and gas exploration and production activities in the UKCS (OGA, 2016).[1] To this end, a significant aspect of the strategy should be to unlock the potential of the many small, undeveloped and economically marginal fields in the province. The economic viability of these fields is hindered by their relatively smaller sizes and/or their remoteness from suitable existing infrastructure as long field-to-infrastructure tie-back lines can be prohibitively expensive. There are over 340 such fields in the UKCS, consisting of predominantly oil, predominantly gas, or condensates; with a total technical capacity of about 3.4 billion barrels of oil equivalent. The challenges facing the economic viability of these fields predate the recent global oil and gas price collapse following the coronavirus/COVID-19 pandemic. However, the steep oil and gas price fall since the pandemic has further contributed to the already existing challenges of the economics of developing these fields. A recent study by Kemp and Stephen (2020) shows that the oil and gas price collapse since the pandemic will likely lead to a significant fall in medium- and long-term production and investment in the UKCS in the period 2019 - 2050. Recent OGA forecasts also show a 26.81% predicted decline in crude oil production in the UKCS over the next five years (OGA, 2020). As a result, new ways of enhancing the economic viability of marginal fields in the UKCS must be explored in order to improve the investment outlook of the province.

From the standpoint of operators, clustering these fields into unit developments with shared communal infrastructure (e.g. subsea manifolds, umbilicals, trees, pipelines) has been advocated as an innovative means of reducing development and operating expenditures through economies of scale, thereby unlocking their economic viability (OGA, 2019b; Kemp and Stephen, 2019.a). Attanasi and Freeman (2005), US EIA (2016) and Kemp and Stephen (2019.a) provide evidence of these economies of scale in the development and operation of oil and gas fields. Figure A1 in Appendix A shows an illustrative example of cluster versus standalone developments, showing for the cluster development scenario the sharing of a single manifold and a single pipeline from the manifold to a processing hub. In addition to clustering, use of emerging standalone storage and processing technologies may also serve as low cost alternatives to traditional field tie-back lines to existing infrastructure, thereby further enhancing the reach and economic viability of remoter fields. Some emerging technologies include unmanned production buoys, dynamically positioned floating systems, etc. (OGA, 2019b). In the current low oil and gas price environment, emphasis on cost reduction strategies could play a significant role in unlocking the economic potential of the mature UKCS province, towards the achievement of the industry's wider MER goal.

Despite the significant potential gains from clustering, it is notable that after many decades and with considerable technological advancements in this area, cluster developments have not been undertaken widely. The literature on the unitisation of oil and gas fields and transaction costs in private contractual agreements provide some explanations as to why this might be the case (Coase, 1960; Hannesson, 2000; Libecap & Wiggins, 1985; Wiggins & Libecap, 1985). The marginal oil and gas fields are owned by multiple license holders. In such circumstances,

[1] The OGA (2016) defines economically recoverable reserves as 'those resources which could be recovered at an expected (pre-tax) market value greater than the expected (pre-tax) resource cost of their extraction, where costs include both capital and operating costs but exclude sunk costs and costs (such as interest charges) which do not reflect current use of resources'.

significant information asymmetries between the different licensees may lead to stagnation in the initiation and/or successful completion of the complex contractual agreements required to facilitate cluster developments. These information asymmetries may be in respect of estimated reserve volumes, value of reserves, investment and operating expenditures, relevant determinants of economic viability, and other such sources of lease heterogeneity. Negotiations between parties may be hindered by important details such as (1) the allocation formula for sharing the costs and profits realised from a cluster development, (2) the need to adjust investor shares when information about the relative values of individual fields to a cluster becomes available during production, etc., hence leading to private contractual failures. Some license holders may have a deliberate strategy of holding out from early participation in a cluster in order to later obtain concessions from early participating parties, hence stalling the potential for agreements. In this regard, policies, regulations and business models structured to surmount information asymmetries between parties and to reduce transaction costs may facilitate agreements towards the realisation of cluster developments in the UKCS.

From the standpoint of the UK government, several instruments, when appropriately designed and implemented, incentivise operator behaviour towards realisation of the MER goal. Taxation and associated allowances have been used to influence investors' outlook for exploration and production activity in the UKCS. In this respect, two related taxes currently apply to the UK oil and gas industry. These are the Ring Fence Corporation Tax (UK Government, 2019.a), currently levied at 30% of field taxable income; and the Supplementary Charge (UK Government, 2019.b) which is currently levied at 10% of field taxable income after an Investment Allowance deduction. The most relevant allowances for tax relief purposes are the Capital Allowances for development expenditures, the Ring Fence Expenditure Supplement which is currently set at 10% compound interest on losses carried forward, and the Investment Allowance for the Supplementary Charge which is currently awarded at 62.5% of development expenditures (UK Government, 2019.c). To avoid double counting of reliefs, the Investment Allowance for Supplementary Charge does not apply when the Ring Fence Expenditure Supplement is being used.

In this paper, we develop a detailed mathematical optimisation model to examine the potential of cluster developments in unlocking field economic viability, taking into consideration the current UK taxation regime. At the existing levels of taxation, this analysis gives operators an indication of the effects of increased internal efficiencies on field economics by way of the economies of scale afforded through clustering.

In addition, an appreciation of the sensitivity of the economics of the marginal fields to market conditions is critical. The literature on investment under uncertainty highlights the role of uncertainty in investment behaviour in general, but also more specifically on depletable natural resources (Dixit, Dixit, & Pindyck, 1994; Elder & Serletis, 2010; Maghyereh & Abdoh, 2020). We therefore simulate our model to examine the sensitivity of the economics of cluster developments to market conditions. We focus on sensitivity of the economics of the fields to oil and gas prices as these are likely to be the most important sources of market uncertainty affecting investors' behaviour.

Our results show that relative to standalone developments, cluster developments offer a unique opportunity to unlock the economic potential of many of the small and presently undeveloped oil and gas fields in the UKCS. At the existing levels of costs, prices and taxation, cluster developments facilitate the unlocking of up to 8.70 times the value from standalone developments in post-tax net present value (NPV) terms, with about $18.05 billion in total NPV to be unlocked across the UKCS province. This is higher in pre-tax NPV terms, with cluster developments facilitating the unlocking of up to $36.97 billion across the province, compared to only $7.76 billion for standalone developments. Sensitivity analysis shows that the economics of the marginal fields exhibit significant sensitivity to market oil and gas prices. Across the UKCS province, up to $30.78 billion in post-tax NPV is realised when oil and gas prices are favourable ($60/bbl and 40 p/therm respectively), but only $7.06 billion is realised when prices are unfavourable ($30/bbl and 20 p/therm respectively). In terms of actions that are in investors' direct control however, use of clustering as a cost reduction strategy makes the most significant difference if the MER goal in the UKCS province is to be realised in the current low oil and gas price environment. Our results highlight the need for the UK government, oil and gas operators and the allied industry institutions to focus on clustering as a cost reduction strategy for oil and gas developments in the UKCS.

The rest of the paper is organised as follows; Section 2 introduces our methodology, with a description of our model and underlying assumptions. Section 3 introduces our data whilst Section 4 introduces our results and discussion. Section 5 concludes the paper.

2 Methodology

In this section, we introduce and describe a detailed mathematical optimisation model which determines optimal clustering and production of marginal UKCS fields through the NPV investment hurdle criterion. This criterion is consistent with the stated MER goal of the UK government and allied oil and gas industry bodies. Our model is novel in three respects; (1) it combines network optimisation modelling techniques (allowing for endogenous networking of fields to form clusters) with discounted cashflow optimisation modelling; (2) it fully captures the current UK taxation regime for new developments in the UKCS; and (3) it resolves three dimensions of optimisation namely endogenous optimal clustering of fields, endogenous optimal development of fields and endogenous optimal production of fields.

2.1 The Model

2.1.1 Equations defining field-to-cluster networks

Let i represent a set of small and undeveloped fields; j represent a cluster of these fields and δ_{ij} represent an endogenously determined binary variable indicating field i is optimally connected to cluster j. For field i, let TFS_i represent the exogenous total field size (mmboe) and let d_{ij} represent the exogenous distance (km) to cluster j. For cluster j, let CS_j represent the endogenous cluster size (mmboe). We define field connections to clusters and cluster sizes as follows;

$$\sum_j \delta_{ij} \leq 1 \ \forall \ i \tag{1}$$

$$\sum_j \left(d_{ij} \cdot \delta_{ij}\right) \leq 25 \ \forall \ i \tag{2}$$

$$CS_j = \sum_i (TFS_i \cdot \delta_{ij}) \;\; \forall \; j \tag{3}$$

Equation (1) states that each field is connected to a maximum of one cluster. Endogenous binary variable δ_{ij} takes a value of 1 if field i is endogenously connected to cluster j and takes a value of 0 otherwise. Equation (2) imposes a constraint on the Euclidean distance between a field and its associated cluster. Following Kemp and Stephen (2019.a), we specify a maximum field-to-cluster distance of 25km so that all fields that are endogenously connected to a cluster are within a 25km radius of the cluster infrastructure. Equation (3) defines the endogenous size of a cluster which is integral to establishing the channels of the economies of scale effects of clusters in our model. Specifically, the larger the size of a cluster, the lower the development and operating expenditure of the cluster, and vice versa.

2.1.2 Equations defining development and operating expenditures and associated tax reliefs

The current UK taxation regime has important implications for the economics of new oil and gas developments with regards to investors' eligibility and timing of investment tax reliefs. As such, modelling of UKCS investments proceed on explicit assumptions about the tax paying positions of the investor. We consider the case of an investor in an existing tax paying position so that s/he is able to benefit from early investment tax reliefs.[2]

Hence let φ_j represent an endogenous binary variable indicating the development status of cluster j (i.e. whether a cluster is developed or not); DE_j^{unit} (\$/bbl) represent the endogenous unit development expenditure of cluster j and DE_j^{total} (\$ million) represent the endogenous positive continuous variable indicating the total development expenditure of cluster j. The total development expenditure of cluster j includes drilling and completion expenditures of production and completion wells as well as the expenditures associated with the installation of cluster infrastructure (e.g. pipelines, manifold, processing hub, etc.). Now let x_{jt} represent an endogenous positive continuous variable indicating production (mmboe) in cluster j in period t; such that;

$$\sum_t x_{jt} - BigM \cdot \varphi_j \leq 0 \;\; \forall \;\; j \tag{4}$$

$$DE_j^{unit} = DE^{intercept} + DE^{slope} \cdot CS_j \;\; \forall \; j \tag{5}$$

$$DE_j^{total} = DE_j^{unit} \cdot CS_j \cdot \varphi_j \;\; \forall \; j \tag{6}$$

$DE^{intercept} > 0$ and $DE^{slope} < 0$

where $BigM$ is a large positive number, and $DE^{intercept}$ and DE^{slope} are the intercept and slope of a straight line relating the unit development expenditure of a cluster as a function of the size of the cluster. Equation (4) captures the development status of a cluster such that φ_j

[2] The implication of this assumption is that the economics of new developments of marginal UKCS fields is enhanced relative to a scenario where the investor is assumed to have no existing tax paying positions.

takes a value of 1 if a cluster j is developed and is producing (i.e. $\sum_t x_{jt} > 0$), and takes a value of 0 otherwise.[3] Data provided in Attanasi and Freeman (2005) suggest that a declining straight-line function approximates the economies of scale inherent in oil and gas developments of the range of small sizes considered here, although for a wider range of field sizes an exponentially declining function emerges, as shown in Figure 1.

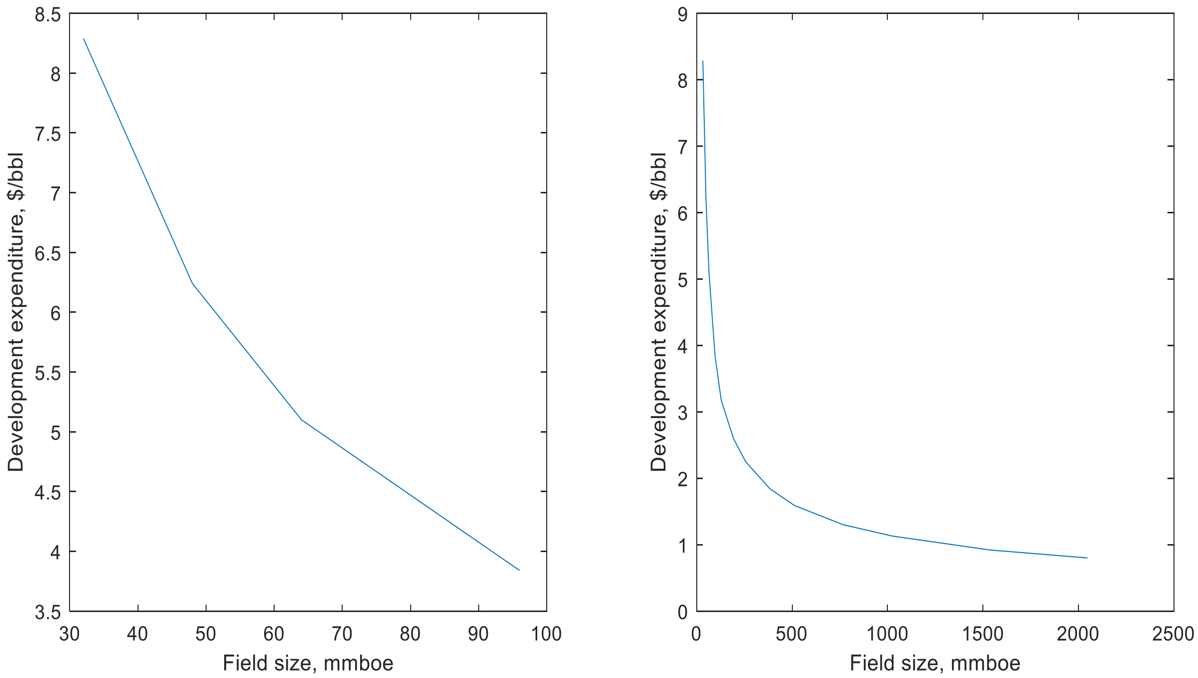


Figure 1: Economies of scale in oil and gas field developments, in 2003 dollars (Source: Author plots based on data in Attanasi and Freeman, 2005; see page 35)

We hence model the unit development expenditure of a cluster as a declining straight-line function of the reserve size of the cluster, as shown in equation (5). Recall that the reserve size of a cluster is defined by the set of equations (1 – 3). Equation (5) is the first of the sources of the economies of scale effects of clustering in our model. It channels through to lower unit development expenditures for larger clusters, and vice versa. By equation (6), only developed and producing clusters have non-zero total development expenditures.

There are also economies of scale effects for the annual operating expenditures[4] during the production phase of a cluster. Following Kemp and Stephen (2020), we model annual operating expenditures as a percentage of the total development expenditure of a cluster. Similar to the treatment of the development expenditure above, we model the annual operating expenditure on a straight-line declining schedule, with the percentage decreasing with higher cluster reserve sizes. Hence let $OE_j^{percent}$ (%) represent the percentage of development expenditure that makes up the annual operating expenditure of a cluster j, and let OE_j^{total} ($ million) represent the total annual operating expenditure of a cluster, such that;

[3] Use of the large positive number $BigM$ in equations (4) and (15) is an integer programming formulation trick that forces the associated binary variables to take a value of 1 when production is nonzero.

[4] Annual operating expenditures include labour, supervision, overhead and administration, well service and workovers, facilities maintenance and insurance, transportation, communications, catering, supplies, etc.

$$OE_j^{percent} = OE^{intercept} + OE^{slope} \cdot CS_j \;\; \forall \; j \tag{7}$$

$$OE_j^{total} = OE_j^{percent} \cdot DE_j^{total} \;\; \forall \; j \tag{8}$$

$OE^{intercept} > 0$ and $OE^{slope} < 0$

where $OE^{intercept}$ and OE^{slope} are the intercept and slope of a straight line relating the operating expenditure of a cluster as a function of the size of the cluster. Equation (7) is the second of the sources of the economies of scale effects of clustering in our model. Through equation (8), it channels to lower unit annual operating expenditures for larger clusters, and vice versa.

Regarding Capital Allowances, our model investor gets full tax relief in the first year of investment. Let CA_j^{total} represent an endogenous positive continuous variable indicating the total capital allowance ($ million) for cluster j; $CT_j^{taxSavings}$ represent first year Ring Fence Corporation Tax savings due to Capital Allowances ($ million), and $SC_j^{taxSavings}$ represent first year Supplementary Charge tax savings due to Capital Allowances ($ million), such that;

$$CA_j^{total} = DE_j^{total} \;\; \forall \; j \tag{9}$$

$$CT_j^{taxSavings} = ct \cdot CA_j^{total}{}_j \;\; \forall \; j \tag{10}$$

$$SC_j^{taxSavings} = sc \cdot CA_j^{total} \;\; \forall \; j \tag{11}$$

where ct and sc are the exogenous Ring Fence Corporation Tax and Supplementary Charge rates (%) respectively.

Equation (9) defines the Capital Allowances of a cluster as the total development expenditure of the cluster, as is the case in the UK tax system for offshore oil and gas operations. Equations (10 – 11) calculate total first year investor tax savings on Ring Fence Corporation Tax and Supplementary Charge respectively.

Regarding Investment Allowance, let IA_j^{total} represent an endogenous positive continuous variable indicating the total Investment Allowance ($ million) for cluster j; and let IA_{jt}^{annual} represent an endogenous positive variable indicating the Investment Allowance ($ million) applied for tax relief purposes for cluster j in period t, such that;

$$IA_j^{total} = ia \cdot DE_j^{total} \;\; \forall \; j \tag{12}$$

$$\sum_t IA_{jt}^{annual} \leq IA_j^{total} \;\; \forall \; j \tag{13}$$

where ia is the exogenous Investment Allowance rate (%).

Equation (12) defines the total Investment Allowance available to a cluster. Equation (13) states that the total sum allocations of Investment Allowances over the life of a developed cluster must be less than or equal to the cluster's total Investment Allowance. This ensures that a cluster development is not utilising more in Investment Allowance than it is eligible for. Equations (4 – 13) capture the development and operating expenditures of a cluster, as well as the allowances available to the investor through the current UK tax system.

2.1.3 Equations controlling cluster production

Following Adelman (1990), we assume an exponentially declining cluster production and depletion function. Let θ_{jt} represent an endogenous binary variable indicating the operational status of cluster j (i.e. whether it is producing or not) in period t; and ρ represent a positive exogenous parameter indicating cluster depletion rate. We assume a common depletion rate ρ for all clusters. Given these variables and parameters, we define the equations and constraints controlling optimal production as follows;

$$x_{jt} = \left[CS_j \cdot \rho \cdot exp\left(-\rho \cdot (t-1)\right)\right] \cdot \theta_{jt} \;\; \forall \;\; j,t \tag{14}$$

$$x_{jt} - BigM \cdot \theta_{jt} \leq 0 \;\; \forall \;\; j,t \tag{15}$$

$$\sum_t x_{jt} \leq CS_j \;\; \forall \;\; j \tag{16}$$

Equation (14) captures the exponentially declining cluster production and depletion profile. Equation (15) defines the endogenously determined binary variable θ_{jt} which takes a value of 1 if cluster j is endogenously operationalised for production in period t (i.e. $x_{jt} > 0$). Equation (16) imposes a constraint on the total production from each cluster such that each cluster produces up to its economic limit only, and below its endogenous size. Equations (14 – 16) capture the endogenous production path of a cluster. This determines the annual income statements of a cluster as discussed below.

2.1.4 Equations defining revenues and cashflows

The following equations outline definitions and constraints capturing the income statement for each cluster in each operational period;

$$R_{jt} = price^{oil} \cdot prop_j^{oil} \cdot x_{jt} + price^{gas} \cdot prop_j^{gas} \cdot x_{jt} \;\; \forall \;\; j,t \tag{17}$$

$$OE_{jt}^{annual} = OE_j^{total} \cdot \theta_{jt} \; \forall \;\; j,t \tag{18}$$

$$PTP_{jt} = R_{jt} - OE_{jt}^{annual} - CA_{jt}^{annual} \; \forall \;\; j,t \tag{19}$$

$$TICT_{jt} = PTP_{jt} \;\; \forall \;\; j,t \tag{20}$$

$$TISC_{jt} = PTP_{jt} - IA_{jt}^{annual} \;\; \forall \;\; j,t \tag{21}$$

$$tax_{jt} = \max\left[0, ct \cdot TICT_{jt} + sc \cdot TISC_{jt}\right] \forall \;\; j,t \tag{22}$$

$$CF_{jt} = PTP_{jt} - tax_{jt} \;\; \forall \;\; j,t \tag{23}$$

where

Variable/parameter	**Description**
R_{jt}	Total revenues of cluster j in period t
$price^{oil}, price^{gas}$	Price of oil and price of gas respectively
$prop_j^{oil}, prop_j^{gas}$	Proportion of oil and proportion of gas in cluster j respectively
OE_{jt}^{annual}	Operations expenditure of cluster j in period t
PTP_{jt}	Pre-tax profit of cluster j in period t
CA_{jt}^{annual}	Capital allowance of cluster j in period t
$TICT_{jt}$	Taxable income for Ring Fence Corporation Tax of cluster j in period t
$TISC_{jt}$	Taxable income for Supplementary Charge for cluster j in period t
tax_{jt}	Tax paid by cluster j in period t
CF_{jt}	Cashflow of cluster j in period t

Equations (17 – 18) define annual revenues and operating expenditures respectively. Revenues are a function of the real price of oil and gas, and the relative proportions of oil and gas produced in a cluster. Notice that the total annual operating expenditure of a cluster OE_j^{total} as calculated in equation (8) and channelled to equation (18) is time invariant, which is consistent with the operating expenditure profiles of UKCS oil and gas operations in the absence of incremental investments (Kemp and Stephen, 2020). We do not consider incremental investments in our model as it is not central to our objective with this paper. Equation (19) defines pre-tax profits. Note that the investor utilises all capital allowances in the first year, as per equations (9 – 11). Equation (20) defines taxable income for Ring Fence Corporation Tax. Equation (21) defines taxable income for Supplementary Charge. Ring Fence Corporation Tax is levied on pre-tax profits, whilst the Supplementary Charge allows for the endogenously determined Investment Allowance to be deducted from pre-tax profits, as shown in equation (21). Minimum tax paid in each period is 0, but maximum is levied as shown in equation (22). Equation (23) captures cashflows for each cluster in each operational period. The cashflows are used in the determination of the overall objective of maximising NPV, as shown next.

2.1.5 Objective function

Assuming the case of a single operator-owner of a set of marginal fields, our objective function is formulated as follows;

$$\text{maximise} \quad NPV = -\sum_j DE_j^{total} + \sum_j \left(CT_j^{taxSavings} + SC_j^{taxSavings}\right) + \sum_{j,t} \frac{CF_{jt}}{(1+r)^{t-1}} \tag{24}$$

where r is discount rate. Notice in the objective function equation (24) that the economies of scale effects of networking small fields into larger clusters is channelled through to lower total development expenditures per barrel of produced reserves; as well as lower total operating expenditures per barrel of produced reserves, which in turn enhance cashflows and subsequently the NPV.

Other important but more nuanced definitions and constraints are imposed in the model to better reflect the reality of upstream oil and gas operations and economics. For example, a constraint is imposed in the model to allow only sequential production for each endogenously operationalised cluster, so that a start-stop-start production sequence is disallowed, as follows;

$$\theta_{j,t-1} \geq \theta_{jt} \;\; \forall \;\; j, t-1 \qquad (25)$$

By this constraint, we have implicitly assumed that the cost of stopping and restarting a cluster is prohibitive, so that once cessation of production occurs, restart is not permissible. We also impose the following constraints to disallow cases where post-tax returns exceed pre-tax returns;

$$CF_{jt} \leq PTP_{jt} \;\; \forall \;\; j, t \qquad (26)$$

$$IA_{jt}^{annual} \leq PTP_{jt} \;\; \forall \;\; j, t \qquad (27)$$

To preserve space, further of such definitions and constraints are not presented here. However, the full model detailing all equations and constraints is available from the authors upon request.

2.2 Model implementation

The mathematical optimisation model is formulated in the General Algebraic Modelling System (GAMS) software and language as a Mixed Integer Non-Linear Programming (MINLP) problem. The model is solved using the SCIP solver in GAMS. Two scenarios of the model are implemented. These are the 'Cluster development' scenario and the 'Standalone (field) development' scenario. The model underlying the cluster development scenario is as presented in Section 2.1 above (i.e. equations 1 – 27), with equation (24) being the objective function and all other equations being constraints and definitions. In the 'Standalone (field) development' scenario, a similar model excluding the equations governing clustering (i.e. equations 1 – 3), is implemented.

3 Data

We source UK Oil and Gas Authority (OGA) and Oil and Gas Technology Centre (OGTC) data for 349 marginal undeveloped oil and gas fields in the UKCS. The geographical positioning of these fields, estimated field sizes, field types (e.g. predominantly oil, predominantly gas, or condensates), etc. are documented in the data. The overall volume of undeveloped oil and gas resource across the 349 fields is about 3415.82 mmboe. The number and volumes of the oil and gas fields across the various regions of the UKCS are summarised in Table 1.

Location	Number of undeveloped fields	Potential reserves, mmboe (P50 estimates)
Central North Sea and Moray Firth (CNS/MF)	156	1667.83
Southern North Sea (SNS)	72	303.38
Northern North Sea (NNS)	45	441.41
West of Shetland (WOS)	23	887.40
Other	53	115.8
Total	**349**	**3415.82**

Table 1: Number and volume of undeveloped marginal oil fields by UKCS regions (Source: OGA and OGTC, 2019)

Figure 2 shows the distribution of the fields and their sizes across the various regions of the UKCS. The average field size in the CNS/MF and NNS regions are 11.43 mmboe and 8.89 mmboe respectively. In the SNS and WOS regions, average sizes are 4.52 mmboe and 38.85 mmboe respectively. Few fields in the CNS/MF and WOS regions are over 100 mmboe. More than 75% of the reserves in the CNS/MF and NNS regions are oil reserves. In the WOS region, about 58% of reserves are oil. The SNS region consists of gas reserves only.

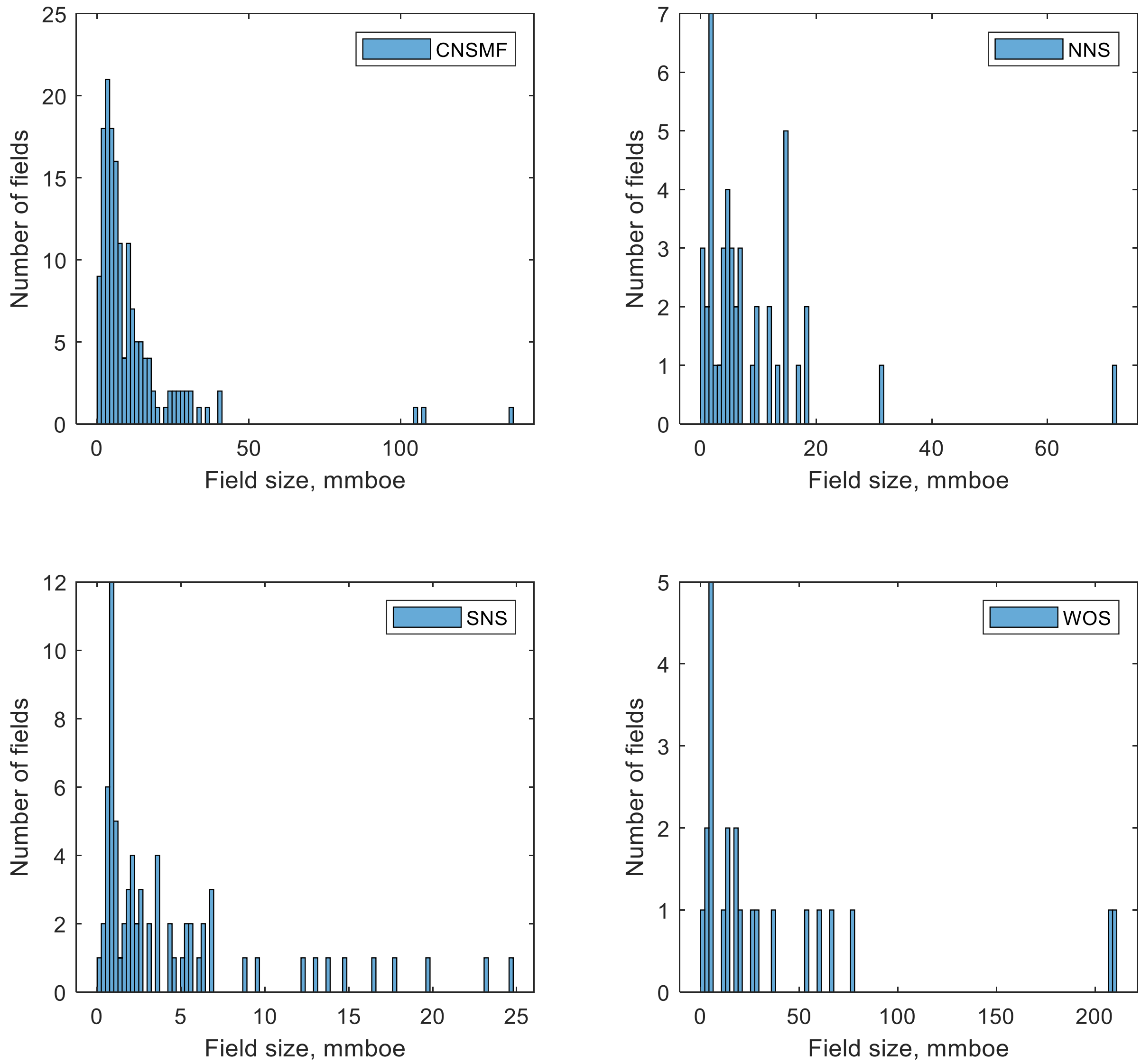


Figure 2: Distribution of the marginal fields and their sizes (mmboe) across the UKCS

To calibrate our model, we use the base parameter values shown in Table 2.

Parameter	Base Case Values	Source
Oil price (real, long run), $/bbl	45	Within range of UK OBR (2020) and US EIA (2020) estimates
Gas price (real, long run), p/therm	30	Within range of UK OBR (2020) and US EIA (2020) estimates
Ring Fence Corporation Tax, %	30	UK Government, 2019.a
Supplementary Charge, %	10	UK Government, 2019.b

Investment Allowance for Supplementary Charge, %	62.50	UK Government, 2019.c
Field decline rate from plateau, %	20	Kemp and Stephen, 2019; Kemp and Stephen, 2020
Real discount rate, %	10	Kemp and Stephen, 2019; Kemp and Stephen, 2020

Table 2: Model base and simulation parameter values

Development expenditures ($/bbl, real) are differentiated by UKCS regions. We use data provided by Kemp and Stephen (2019.b), as shown in Table 3.

Unit development expenditure, $/bbl	**CNS/MF**	**NNS**	**SNS**	**WOS**
Mean	14.27	17.16	16.44	19.85
Min	5.71	6.86	6.58	7.94
Max	22.83	27.46	26.30	31.77

Table 3: Unit development expenditures, $/bbl (Source: Kemp and Stephen, 2019.b)

As previously mentioned, unit development expenditure of fields and clusters is modelled on a declining straight-line schedule as a function of the size of a field or cluster (see equation 5). This is the source of the economies of scale effects of clustering in our model. A similar schedule is implemented to capture economies of scale effects in annual operating expenditures, as shown in equation (7).

To determine the parameters of the declining straight-line schedule for unit development and operating expenditures, we implement a separate simple model to find the largest possible 25km-radius cluster in each region. This cluster assumes the minimum unit development expenditure in Table 3 for that region. The cluster also assumes the minimum annual operating expenditure as a percentage of the development expenditure, taken to be 5% in all regions (Kemp and Stephen, 2019.a). The smallest field in a region assumes the maximum unit development expenditure in Table 3; and a maximum annual operating expenditure as a percentage of the development expenditure, taken to be 10% in all regions (Kemp and Stephen, 2019.a). The estimated declining straight-line intercept and slope for each region's unit development expenditure is shown in Table 4.

Straight-line unit development expenditure parameters	**CNS/MF**	**NNS**	**SNS**	**WOS**
Development expenditure Intercept, $/bbl	22.87	27.52	26.30	31.82
Development expenditure Slope	-0.08	-0.21	-0.20	-0.04

Table 4: Parameters of declining straight-line schedule for unit development expenditure

By this aspect of our modelling, we have endeavoured to capture two important sources of cost heterogeneity; (1) differences in unit development expenditures across the various UKCS regions; and (2) the unit development and operating expenditures as a function of the sizes of fields and clusters across the province in order to capture economies of scale effects.

4 Results and Discussion

We separately model each region of the UKCS to determine optimal development and production under the 'cluster development' and 'standalone (field) development' scenarios. We first discuss the results from the investor perspective regarding the benefits of clustering. We then discuss the sensitivity of the economics of clustered developments to oil and gas market conditions. Specifically, we consider sensitivity to oil and gas market prices.

4.1 The Investor: 'Cluster' vs 'Standalone' developments

Figure 3 shows the base case optimal number of developed fields under the 'cluster development' and 'standalone (field) development' scenarios for each UKCS region. Further details are provided in Table 6 under Appendix A.

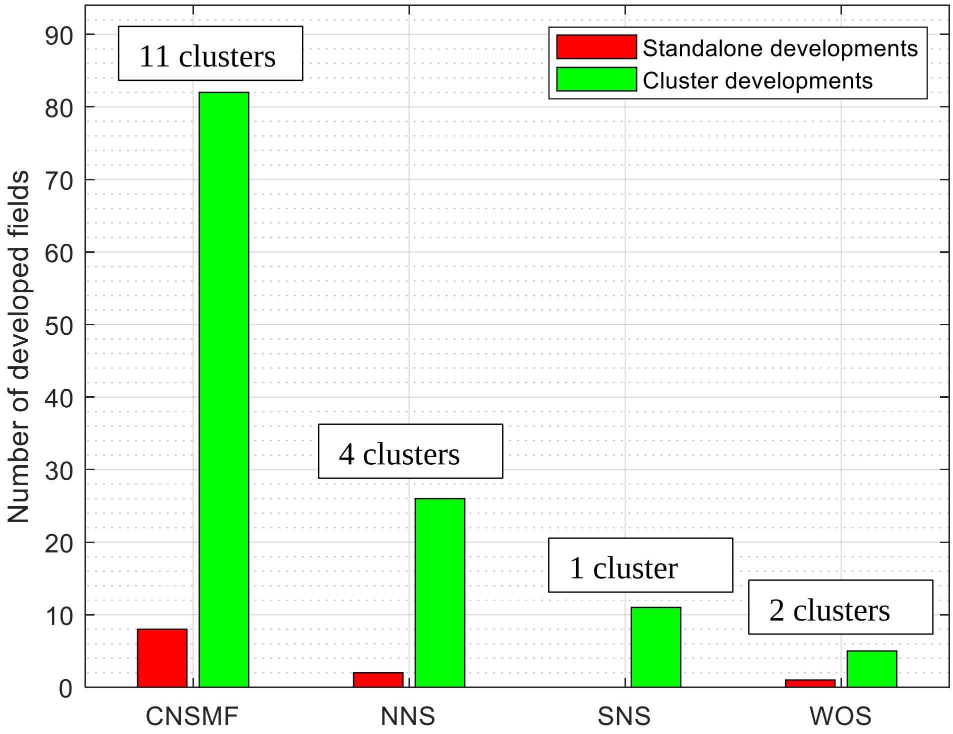


Figure 3: Base case results – Number of developed fields; Standalone vs Cluster development scenarios

In the CNS/MF region under the standalone field development scenario, only 8 of the 156 available fields are developed representing 5.13% of the fields in the region. Under the cluster development scenario however, 82 fields representing 52.56% of fields and constituting 11 clusters are developed. Figure 4 shows a GIS map rendition of the results. The result highlights the economies of scale effects and advantages of clustering in unlocking the economic potential of the fields. Results for the NNS, SNS and WOS regions of the UKCS also show these effects (see Figure 5, Figure 6 and Figure 7 for GIS map rendition of results), with clustering allowing for more fields, and consequently more reserves to be developed. Economies of scale effects of clustering are further highlighted in the SNS region where standalone developments are not feasible, but up to 11 fields can be developed under one cluster. Also, in the WOS region, only two clusters are developed, in part due to the high development expenditures in that region and the dispersed and remote nature of many of the fields such that they are out of the proximity range (25km) required for clustering. Total number of fields and production in each region is greater for the cluster development scenario compared to the standalone field development scenario, with over 50% of fields developed in the CNS/MF and NNS regions under the cluster development scenario. Overall production across the five regions for the cluster development scenario is 2071.34 mmboe, compared to only 780.93 mmboe for the standalone field development scenario.

Figure 4: Optimal cluster developments of small undeveloped fields in the Central North Sea and the Moray Firth region (CNS/MF)

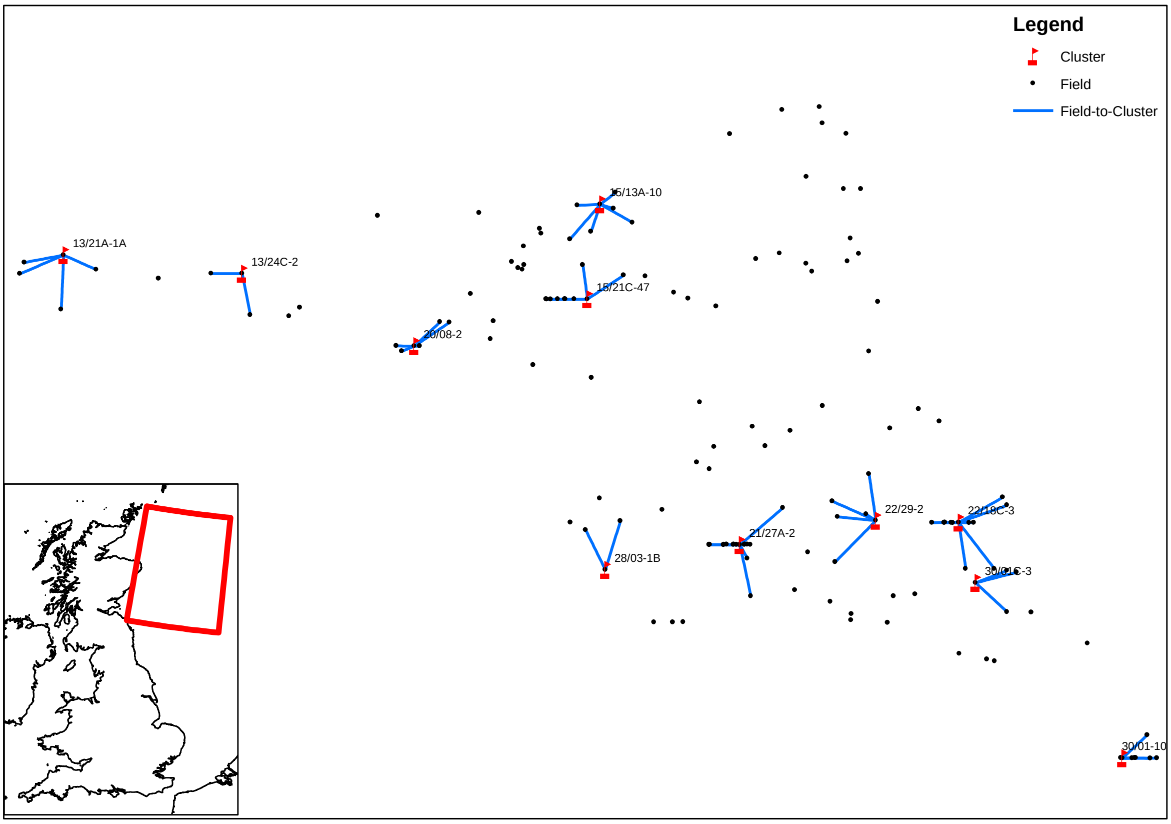


Figure 5: Optimal cluster developments of small undeveloped fields in the Northern North Sea region (NNS)

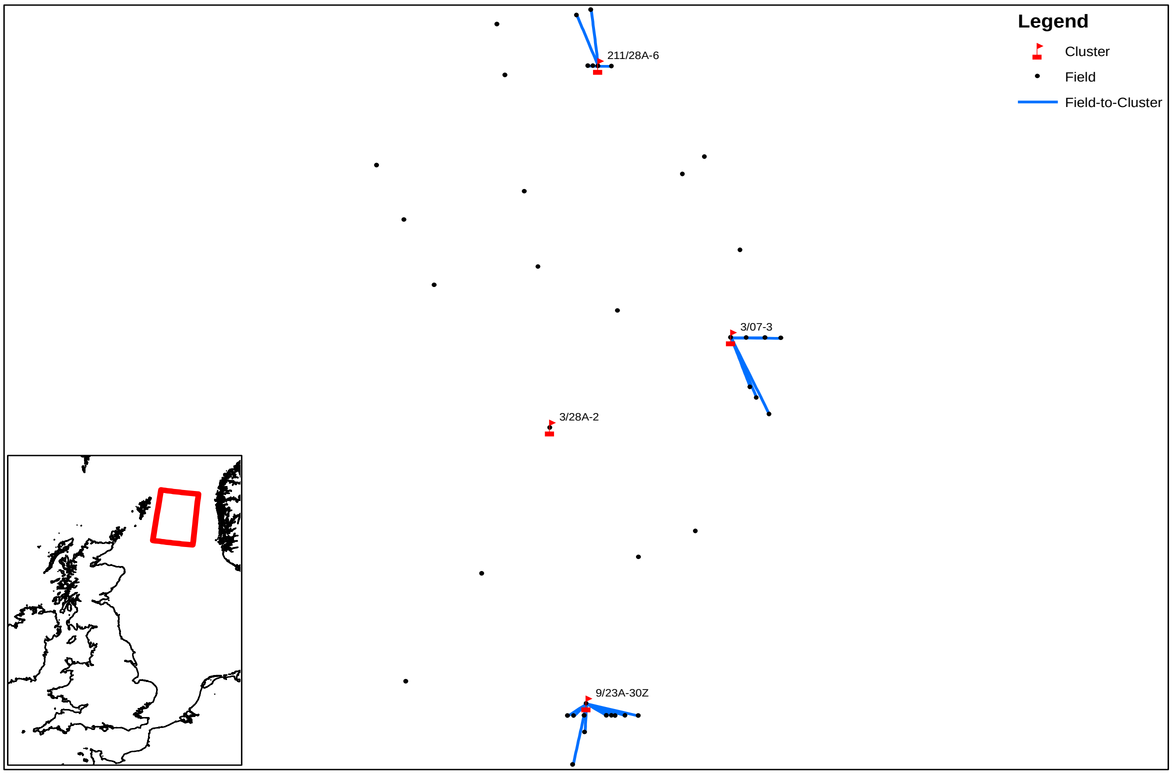


Figure 6: Optimal cluster developments of small undeveloped fields in the Southern North Sea (SNS)

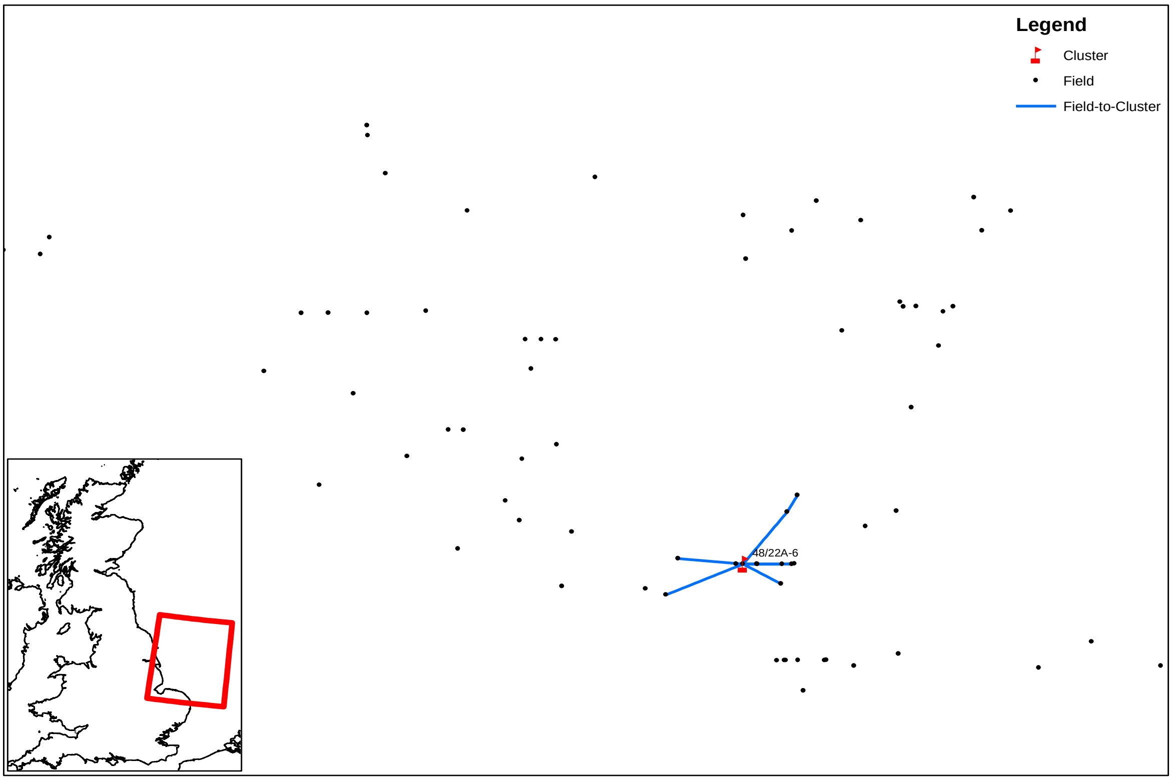
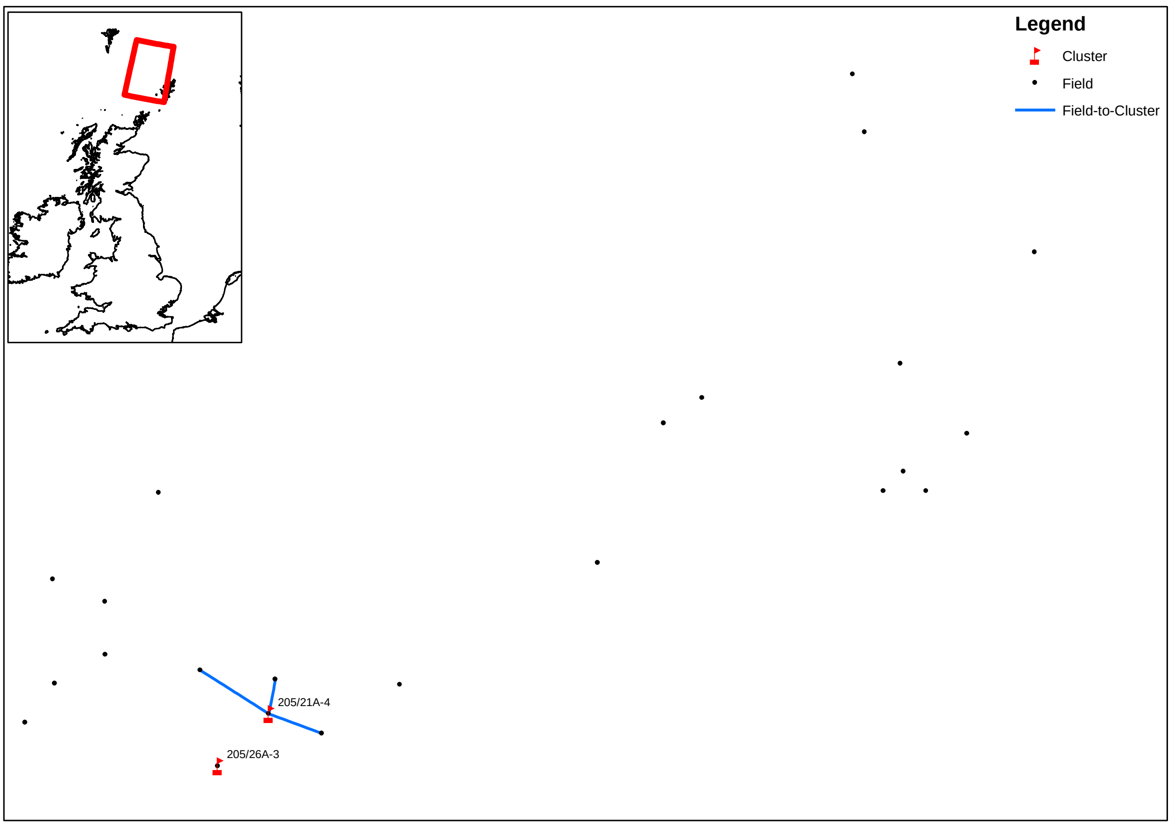


Figure 7: Optimal cluster developments of small undeveloped fields in the West of Shetland (WOS)



Legend

Cluster

Field

Field-to-Cluster

Figure 8 shows the base case investor pre- and post-tax NPVs of optimally developed and produced oil and gas under the two scenarios across the four UKCS regions.

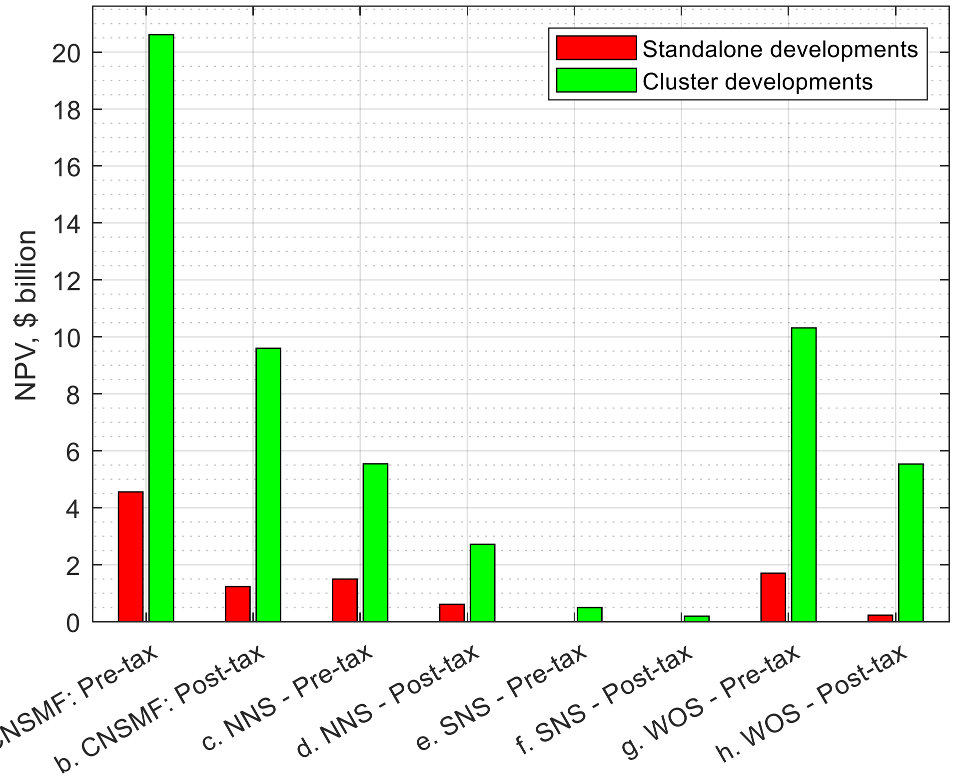


Figure 8: Base case results: Pre- and post-tax NPVs at 10% real discount rate

As expected, the investor pre- and post-tax NPVs of produced reserves under the cluster development scenario is greater than that of the standalone field development scenario in all developed regions. Aggregate pre- and post-tax NPVs under the cluster development scenario across all regions of the UKCS are $36.97 billion and $18.05 billion respectively, compared to only $7.76 billion and $2.07 billion respectively under the standalone field development scenario. This shows that in post-tax NPV terms, cluster developments facilitate the unlocking of up to about 8.70 times the value from standalone field developments across the UKCS.

Given our base model parameter values for taxation, prices and costs, it is shown that compared to standalone field developments, cluster developments offer major benefits across all four regions of the UKCS. The CNS/MF region offers the greatest opportunity to unlock the potential of undeveloped marginal fields in the UKCS, with up to $20.61 billion and $9.60 billion in pre- and post-tax NPVs respectively to unlock from that region.

4.2 The Market: Sensitivity to Oil and Gas Prices

We examine the sensitivity of the economics of clustered developments to market conditions, with focus on oil and gas prices. The level and volatility in these prices are a major driver of the investment climate in the UKCS, especially in relation to marginal fields. Table 5 shows the simulation results for the CNS/MF region, which as shown above offers the greatest reward; and the simulation results for the entire UKCS province based on an aggregation of results over all the individual regions. We use range of oil and gas prices within scope of the UK Office for Budget Responsibility's forecast prices over the next 5 years (UK OBR, 2020) and US EIA (2020) short term outlook estimates. All other parameters (e.g. taxation, costs, etc.) are maintained at their base case values.

Oil price, $/bbl	p/therm	CNS/MF region				UKCS province			
		NPV, $ billion	Number of clusters	Number of fields	Production, mmboe	NPV, $ billion	Number of clusters	Number of fields	Production, mmboe
30	20	3.14	6	57	883.55	7.06	10	82	1558.83
	30	3.58	7	61	1,018.90	7.70	12	97	1778.18
	40	4.10	7	61	1,018.90	8.42	12	97	1778.18
45	20	9.14	11	82	1,265.85	17.43	16	113	1983.65
	30	9.60	11	82	1,269.76	18.05	18	124	2071.34
	40	10.06	11	82	1,269.76	18.76	18	124	2071.55
60	20	16.38	18	100	1,356.78	29.43	31	145	2165.23
	30	16.85	19	104	1,372.38	30.10	33	160	2264.82
	40	17.33	19	104	1,373.39	30.78	33	160	2264.82

Table 5: Sensitivity analysis showing effects of oil and gas prices on post-tax NPV of clustered developments, $ billion

As is to be expected in the CNS/MF region, sensitivity of the economics of clustered marginal developments to oil prices is greater than sensitivity to gas prices due to the greater composition of oil reserves relative to gas in that region. Also, for the entire UKCS province, sensitivity of the economics of the clustered fields is greater for oil prices than it is for gas prices. At favourable oil and gas prices of $60/bbl and 40 p/therm respectively, total post-tax NPV from clustered developments could be as high as $17.33 billion in the CNS/MF region, and $30.78 billion across the whole of the UKCS province. In that scenario, up to 160 fields over 33 clusters can be developed across the UKCS province, producing 2264.82 mmboe, which is about 66.30% of the total reserves in the marginal fields in our data. At unfavourable oil and gas prices of $30/bbl and 20 p/therm however, only $7.06 billion is realisable in total post-tax NPV across the UKCS province hence highlighting the sensitivity of the economics of clustered developments in the UKCS to oil and gas price movements.

5 Conclusion

The overarching goal of the UK government and allied institutions is to maximise economic recovery (MER) from the UKCS province. Being a mature province however, many of its newly discovered or previously appraised but undeveloped fields are small. The economic viability of these fields is hindered by their small sizes and/or their remoteness from suitable existing infrastructure. The recent global oil and gas price collapse following the coronavirus/COVID-19 pandemic has further contributed to the already existing challenges of the economics of developing these fields. As a result, other ways of enhancing the economic viability of the fields must be explored in order to realise their value. Clustering these marginal fields into unit developments with shared communal infrastructure is an innovative means of reducing development and operating expenditures through economies of scale. In this paper, a detailed mathematical optimisation model is developed to examine the potential of cluster developments in enhancing the economic viability of these fields. Sensitivity analysis of the economics of the fields to oil and gas market prices is also examined.

Our base results show that relative to standalone developments, cluster developments offer a unique opportunity to unlock the economic potential of many of the small and presently undeveloped oil and gas fields in the UKCS. At the existing levels of costs, prices and taxation, cluster developments facilitate the unlocking of up to 8.70 times the value from standalone developments in post-tax net present value (NPV) terms, with about $18.05 billion in total NPV to be unlocked across the UKCS province. This is higher in pre-tax NPV terms, with cluster developments facilitating the unlocking of up to $36.97 billion across the province, compared to only $7.76 billion for standalone developments. The CNS/MF region has the greatest potential, with up to $20.61 billion and $9.60 billion in pre- and post-tax NPV respectively to unlock by way of clustering.

Price sensitivity analysis show significant sensitivity of the economics of clustered developments to oil and gas prices. As much of the marginal field reserves across the UKCS province are predominantly composed of oil, there is a higher sensitivity to oil price movements than gas price movements. At favourable oil and gas prices (i.e. $60/bbl and 40 p/therm), up to 66.30% of the reserves across the province is economically recoverable through clustered developments. Total post-tax NPV in such a scenario is about $30.78 billion. At unfavourable prices however ($30/bbl and 20 p/therm), only $7.06 billion in post-tax NPV is realised hence highlighting the significant sensitivity of cluster development economics to oil and gas prices.

Despite the significant potential of cluster developments shown in this paper, there are important barriers to implementing them in the UKCS. As the existing marginal undeveloped fields are owned by multiple investors, one major barrier is the issue of the investors' mis-aligned goals, investment metrics, hurdle rates and/or development plans. This also links to the literature on oil and gas field unitisation where information asymmetry regarding the estimates and value of individual fields has been identified as a major cause of contractual failures in relation to unitised and/or clustered fields. In this regard, early field developers would need to implement the infrastructure necessary for clustering with later fields. However, for early developers to commit to such infrastructure investments, agreements need to be reached with later developments in order to finance the common infrastructure. Third party infrastructure access tariffs may need to be established as part of these agreements.

Government regulations and policies may be needed to facilitate private contracts amongst the multiple owners towards the achievement of clustered developments. A key goal of such regulations and policies should be to surmount the information asymmetries that hinder private contracts. In this regard, the timing of the stage in the resource exploitation process where parties meet to negotiate a plan and an agreement is critical. Evidence from the literature of oil and gas field unitisation suggest that negotiations are likely to succeed in the stage where information asymmetry is at a minimum, notionally before cluster development occurs. Once development has proceeded sufficiently to reveal potential differences in value across leases, private contracting for clustering would be more likely to fail.

Within existing rules, the UK OGA which regulates the UK offshore oil and gas industry has the power to require licensees to collaborate. In extreme circumstances, the OGA can mandate licensees who do not want to collaborate in a cluster, which the OGA finds to be desirable, to market their licence interests to others who have different views. These powers are however not frequently used. To facilitate agreements on clustering, the OGA may need to assume a more proactive stance with these powers.

It may also be necessary to develop business models that eliminate the complications of misaligned multi-investor goals, metrics and plans in order to make the realisation of cluster developments in the UKCS more feasible and likely. One such business model has been proposed by KPMG (2020) in the context of the management of late-life fields, where the ‘ownership’ and ‘operation’ dimensions of multi-owned fields are disentangled so that even as original owners maintain ownership of their fields, the operation of the fields is transferred to companies specialised in late-life field management. This reduces operational costs and enhances value recovery. This model can be adopted to facilitate cluster developments. Original licensees of the marginal fields can maintain ‘ownership’ interest in their fields, but the cluster ‘development and operation’ can be transferred to an external entity. This entity plans, develops and operates the relevant cluster. The entity is essentially a specialised service provider for the owners of the individual fields making up a specific cluster. Multiple such entities may be separately and independently contracted to operate specific clusters. The OGA may proactively use its powers to facilitate such arrangements. Significant cost savings and reduced investment risks may be realised with this business model.

We have shown in this paper that clustering offers the best strategy to unlock the potential of marginal fields in the UKCS, hence contributing to the goal of MER in the province. Our focus has been on the economies of scale effects of clustering in facilitating this goal. Future research would need to look at the effects of the contemporary focus on energy transition and climate change issues on investors’ outlook for marginal field developments in the UKCS.

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Appendix A: Results

Table 6: Summary of results

Region	Type of Development	No. of developed fields	% developed fields	Number of clusters	Total Production, mmboe	Pre-tax NPV, $ bill	Post-tax NPV, $ bill
CNS/MF	Non-Clustered	8	5.13	-	491.20	4.56	1.23
CNS/MF	Clustered	82	52.56	11	1,269.76	20.61	9.60
NNS	Non-Clustered	2	4.44	-	99.09	1.50	0.61
NNS	Clustered	26	57.78	4	283.25	5.54	2.72
SNS	Non-Clustered	-	-	-	-	-	-
SNS	Clustered	11	15.28	1	83.99	0.50	0.19
WOS	Non-Clustered	1	4.35	-	190.64	1.70	0.23
WOS	Clustered	5	21.74	2	434.34	10.32	5.54

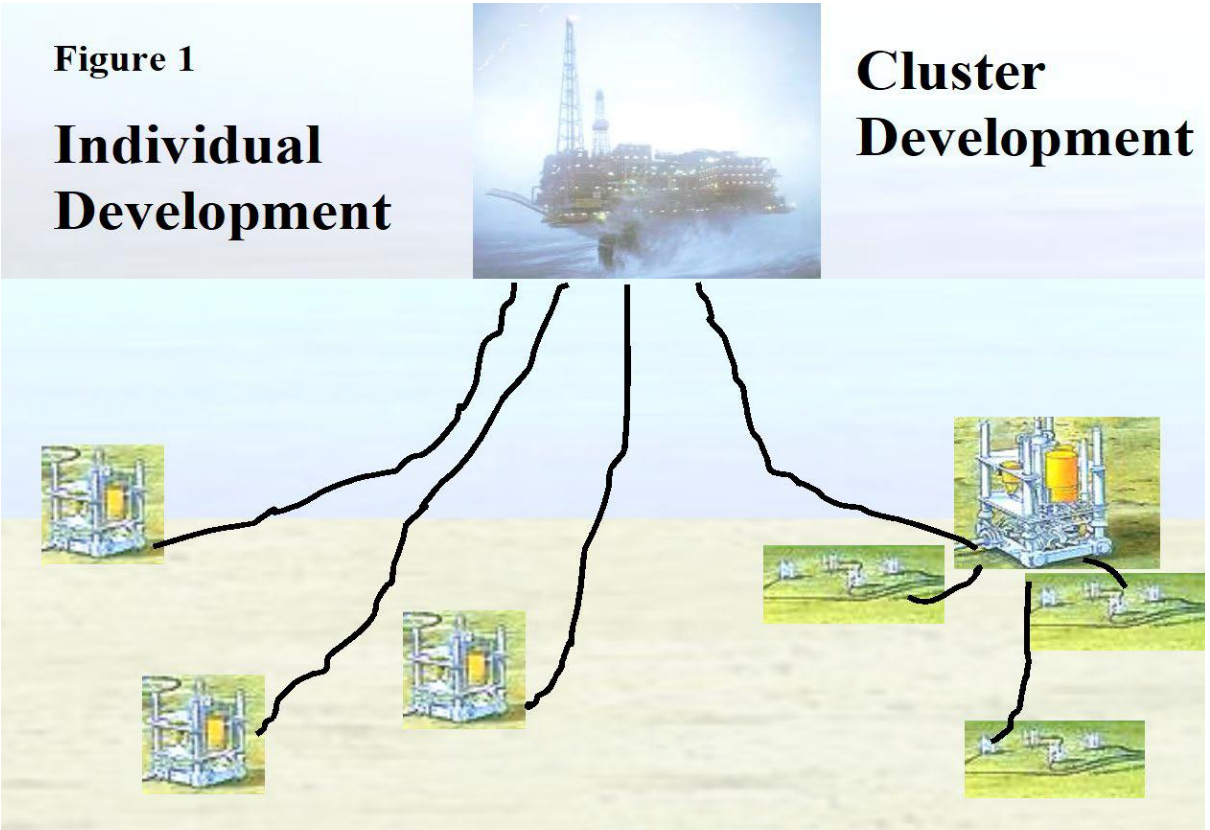

Figure A1: Illustrative example of Cluster versus Standalone Developments (Source: Kemp and Stephen, 2019.a)