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Floating offshore wind and the real options to relocate

Jostein Tvedt [a,b,*,1]

[a] Centre of Ocean Business, BI Norwegian Business School, Oslo, Norway
[b] The Institute of Transport Economics, Oslo, Norway

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ABSTRACT

Real options to relocate may improve the profitability of the floating offshore wind industry. Location and market switching can contribute to mitigating parts of the cost disadvantage of floating versus fixed-bottom offshore wind. The article derives optimal relocation strategies and real options values under uncertainty. Risk factors that may increase the value of relocation options include electricity prices, capacity factors, political uncertainty, collateral valuation, environmental issues and technological progress.

1. Introduction

Offshore wind farms are moving into deeper waters – using floating instead of fixed-bottom structures – as attractive shallow water locations are getting scarcer and deeper waters may offer favourable wind conditions. In contrast to much industry and political enthusiasm, floating offshore wind faces a serious cost disadvantage compared to traditional fossil-based energy sources. Given today's technology and the pre-commercial scale of the existing floating offshore wind farms, there is still some way to go before floating offshore wind will be competitive in terms of levelized cost of energy (LCOE) compared to fixed-bottom wind farms.

The existing floating offshore wind literature does not appear to discuss the value of relocation flexibility. Generally, the focus has been on reducing LCOE, i.e., on minimising the discounted sum of costs over the discounted sum of electricity production over a project's lifetime, and on optimizing technology in light of electricity market dynamics and location and wind conditions. See for example Myhr et al. (2014), Castro-Santos and Diaz-Casas, 2014, Castro-Santos et al., 2016), Papakonstantinou et al. (2019), del Jesus et al. (2017), Aldersey-Williams and Rubert (2019) and Ioannou et al. (2020). The UK Department of Energy and Climate Change and the US Department of Energy's National Renewable Energy Laboratory have both embraced the LCOE perspective. This may partly explain its popularity.

Real options theory (ROT) may be a useful alternative to the LCOE perspective for strategic and valuation purposes. A real option is a right, not an obligation, to take a specific future action at some cost with regards to a real, i.e., non-financial, asset. Real options typically include the option to defer, to grow, to expand, to contract, to shut down, to restart and the options to switch. See Trigeorgis (1996). The ROT approach is well established in the general renewable energy literature. For example, wind industry investments have successfully been studied in a ROT framework by Venetsanos et al. (2002), Lee and Shih (2010), Barroso and Iniesta (2014) and Ritzenhofen and Spinler (2016). In an offshore wind industry setting Himpler and Madlener (2014) discuss optimal strategies for repowering fixed-bottom units using ROT.

This paper focuses on switching options in the floating offshore wind industry. Mossin (1968) seems to be the first to formally study a switching problem under uncertainty. He develops a discrete time model of switching between operating or temporary laying up a vessel under volatile prices and derives the classical hysteresis result of the switching literature. Dixit (1989) is the standard reference of switching under geometric Brownian motion price volatility. He shows how the hysteresis effect is enlarged by an increase in volatility. Tsekrekos (2010) studies the classical switching problem for mean reverting prices and shows how mean reversion in the long run counterbalances some of the effect of volatility on hysteresis.

The floating offshore wind industry may be more attractive than suggested by the LCOE perspective. A floating structure is by design more mobile than a fixed-bottom structure. Mobility may create

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* Corresponding author at: Centre of Ocean Business, BI Norwegian Business School, Oslo, Norway.
E-mail address: jtv@toi.no.
[1] Jostein Tvedt, TØI, Gaustadalleeen 21, N-0349 Oslo, Norway.

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opportunities for optimal relocation under uncertainty. The flexibility to relocate may create value to the floating offshore wind industry in the future in a similar way as flexibility creates value to the crude oil shuttle tanker and offshore oil rig industries today.

The volatility in energy markets may increase going forward due to a global underinvestment in the clean energy transformation. This may create a risk of destabilising volatility. (IEA, 2021). The aftermath of the Covid-19 pandemic contributed to high and volatile electricity, coal and gas prices. Uncorrelated and volatile energy prices typically increase the real options values of relocating energy production facilities. On a macro level relocation may contribute to reducing destabilising regional energy price volatility.

Methodically, this paper is close to the logistic industries literature that has studied the value of switching, e.g., Bjerksund and Ekern (1995), Sødal et al. (2008), Adland et al. (2017b), and Adland et al. (2017a). The paper adds to the offshore wind industry literature by recognising the floating units' ability to switch production locations or regional electricity markets and by deriving optimal relocation strategies under uncertainty.

The paper is organised as follows. Section 2 reviews factors that make relocation in the floating offshore wind industry attractive. Section 3 illustrates how the inherent real options to relocate between two regions can be derived by an established real options framework. Section 4 studies the parameter sensitivity of the relocation model. Section 5 extends the model to three locations and two markets. Section 6 discusses model limitations and potential extensions. Section 7 concludes.

2. Floating offshore wind relocation flexibility

The models below focus on optimal switching between locations and markets under electricity price and capacity factor volatility. Other factors may also affect the value of relocation flexibility. The following list is by no means exhaustive:

i. *Prices and capacity factors*. The cashflows generated by an offshore wind unit depend mainly on electricity prices – market based or feed-in-tariffs – and capacity factors related to operational performance and wind conditions. Market based electricity prices and capacity factors are volatile. The value of the flexibility to relocate can be substantial if medium to long run cash flow volatility is high.

ii. *Costs*. The cost of relocation is a key factor to any relocation strategy. Costs partly depend on technical and organizational solutions and partly on the distance between locations. Both cost levels and cost uncertainty affect the value of flexibility.

iii. *Subsidies*. Subsidies play a part in renewable energy markets. A supportive renewable energy regime may be temporary. The negative effect of unexpected changes to regional feed-in-tariffs may be partly compensated if the physical structures can be relocated. For example, at the end of a subsidy program it may be worthwhile to move the floating offshore wind unit to a new location for the unit's remaining lifetime.

iv. *Finance*. Cheap finance is key to capital intensive industries like offshore wind. In the case of a credit default relocation options may be valuable to a lender, i.e., the options to relocate may increase the value of the unit as debt collateral. For example, the holder of the debt may improve the recovery rate in the case of a default by relocating the unit to a more profitable wind field. In some cases, it may be favourable to physically remove a unit from an unfriendly jurisdiction –from the debt holders' perspective. At present the wind industry attracts green institutional investors. The existence of relocation options may widen the investor base and reduce the funding cost of floating offshore wind compared to immobile energy units.

v. *Technology*. Floating offshore wind technology is at an early stage. As new technologies emerge and better wind data becomes available, there may be a case for sophisticated relocation strategies. New technically superior units may substitute old units. Second-hand units may be moved to new locations. If relocation costs become sufficiently low, we may see relocation internally in portfolios of floating offshore wind parks according to seasonal variations in wind conditions. For example, one turbine configuration may be more optimal during the summer season whereas another may be more optimal during the winter season.

vi. *Environment*. Seasonal relocation may reduce environmental conflicts. The options to relocate may make new areas available that for environmental reasons are off limit today. For example, during tourist seasons or bird migrations units may be relocated to operate elsewhere. Temporary relocation may be an alternative to e.g., Hüppop et al. (2006) recommendations that one should consider abandonment of wind farms in zones with dense bird migration or to turn off turbines during critical migration periods. Seasonal relocation may in some cases reduce conflicts between fisheries and the offshore wind industry. Given the long life of a floating offshore wind unit, gradual changes to local weather conditions due to climate change may eventually trigger relocation.

vii. *Political uncertainty*. Floating offshore wind may represent an attractive solution in coastal regions that are suffering from political instability and are lacking a state-of-the-art energy sector. The potential for withdrawing floating units may mitigate the country risk related to investing in electricity production in politically unstable regions. Floating units may in the future play a role during emergencies, e.g., during a breakdown of vital land-based power generation.

The floating offshore wind industry is in its infancy. At this early stage ROT may not formally guide investment decisions, yet developers may informally take into account the potential for switching deployment in the future.

The first commercial scale floating offshore wind park, the 30 MW Hywind Scotland, was commissioned in 2017. The park is connected to the Scottish electricity grid and is supported by the UK Renewable Obligation Centre subsidy scheme. The Hywind Scotland is likely to stay at location during the lifetime of the turbines or steel floaters. That is, the value of relocation in this case is probably low.

The 88 MW Hywind Tampen is currently under construction. The floating wind park will supply electricity to the Gullfaks and Snorre oil fields. The business idea is to provide renewable energy to the oil fields in order to reduce the carbon footprint of oil production and to cut CO2 taxes.

The Gullfaks and Snorre oil fields are mature – commissioned respectively in 1986 and 1992. The commercial remaining lifetime is probably limited. The Hywind Tampen turbines can typically operate for 25 to 30 years. The technical lifetime of the Hywind Tampen's concrete floaters can easily be more than two times that of the turbines and will likely outlive the oil fields by decades.

Government direct subsidies are close to 60% of the Hywind Tampen investment (Enova and NOx-fund). Depreciation is deductible against oil revenues. Oil related profits in this jurisdiction are taxed at 78%, which makes the cost deductions highly attractive in order to reduce overall taxes. Indirectly most of the Hywind Tampen investment will therefore in less than a decade be paid by the Norwegian Government. Whenever the mature Gullfaks and Snorre oil fields are decommissioned, the Hywind Tampen units may be relocated to new profitable locations and markets. Whenever the turbines are technically or commercially obsolete, the units may be moved to shore and the floaters fitted with new turbines that may operate for another 25 to 30 years. The value of these real options may be substantial.

The largest European land-based wind farm area is located at Fosen peninsula just northeast of the Tampen area. The farms of a total capacity of 1000 MW and an annual production of 3400GWh a year were commissioned in 2020 – just in time to enjoy subsidies via a green certificate program. Partly due to the deadline of the green certificate program construction was commenced despite conflicts with the indigenous Sami population and their traditional nomadic use of the area for reindeer herding during the winter season. In 2021 the grand chamber of the Norwegian supreme court ruled the operating licences of the largest two of the farms a breach of the Sami people's rights in the area. The consequence may be that the parks, i.e., a total of 151 turbine, have to be decommissioned and the infrastructure dismantled.[2] The cost of a forced relocation of a land-based wind park is substantial. The ruling may strengthen the case for floating offshore wind parks in politically or environmentally sensitive coastal areas.

3. An offshore wind relocation real options valuation model

This section applies established ROT to derive the value of relocation flexibility under cashflow volatility for the offshore wind industry.

Let a mobile floating offshore wind unit operate in location b. Let there also be a fixed-bottom unit of equal capacity in location b. The floating unit may be disconnected from location b and moved to an alternative location a. Let the dynamics of the extra revenue earned at any time t in the alternative location a compared to the fixed-bottom unit's location b, X_t, be given by the Ornstein-Uhlenbeck process

$$dX_t = \kappa(\alpha - X_t)dt - \sigma dB_t \tag{1}$$

where dB_t is the increment of a standard Brownian motion, σ is the standard deviation of the change in X_t, α is the mean level of the instantaneous revenue spread between location a and b, and κ is the speed of mean reversion of the revenue spread.

The cost of operating in location a may not be the same as the cost of operating in location b. Let the extra cost of operation in location a at time t be given by a constant number c_a. The extra cost may be a negative number, i.e., in the case that location a has a lower cost level than location b. Compared to a fixed-bottom unit in location b, a floating unit can either earn the same as the fixed-bottom unit in location b or it can move to location a and earn $X_t - c_a$ extra at any time t.

Let the total cost of moving the unit from location b to a to be given by $K^{b\to a}$. This includes the direct costs of disconnecting, moving and reconnecting at the new location, in addition to the loss of revenue generation during the time it takes to move the unit from one grid connection to the next. In the same way, let the total cost of moving the unit from location a to b be given by $K^{a\to b}$. $K^{a\to b}$ may be different from $K^{b\to a}$, but the costs will probably in most cases be rather symmetric.

Let the excess value of operating the mobile floating unit in location a, compared to a fixed-bottom unit in location b, be given by Φ_t^a. Let the excess value of operating the mobile floating unit in location b, compared to a fixed-bottom unit in location b, be given by Φ_t^b. These values represent the extra cash-flows generated in the future from optimally switching between location a and b. That is, let the excess value of the floating unit, at time zero, be given by

$$\Phi(x) = \sup_{\omega} E^Q\left[\int_0^\infty e^{-\rho s}(x_s - c_a)I_a ds - \sum_{j=0}^{N} e^{-\rho\theta_j}K^{\xi_j}\right] \tag{2}$$

where ρ is a constant discount factor that represents the real interest rate and the rate of depreciation of the unit. The controls ω are given by $\omega = (\theta_1, \theta_2, \ldots\theta_N; \xi_1, \xi_2, \ldots\xi_N)$, $N < \infty$, where θ_j is the time of control number j, and ξ_j represents the direction of the move of the production unit at control j, i.e., either $b \to a$ or $a \to b$. I_a is an indicator function that takes the value one if the unit is operating in region a and takes the value zero if the unit is operating in region b. Q is a certainty equivalent probability measure.

In order to incorporate risk aversion, the framework of Bjerksund and Ekern (1995) is useful. In a capital asset pricing setting let

$$dB_t = d\widehat{B}_t - \lambda dt \tag{3}$$

where $\widehat{B}_t$ is a standard Brownian motion under the certainty equivalent Q probability measure, i.e., the increment $d\widehat{B}_t$ has a mean of zero and a variance of dt under the Q measure. The constant λ is the market price of risk. The Ornstein-Uhlenbeck process under the Q measure is then given by

$$dX_t = \kappa(\widehat{\alpha} - X_t)dt - \sigma d\widehat{B}_t \tag{4}$$

where the risk adjusted mean level of the price process is given by $\widehat{\alpha} = \alpha - \frac{\sigma\lambda}{\kappa}$.

Solutions to optimal control problems similar to (2) have been studied in the ROT literature. See e.g., Dixit and Pindyck (1994). Mathematically the problem is close to Sødal et al. (2008). However, they solve the problem for a risk neutral agent.

The autonomous property of relations (1) and (2) implies that the optimal controls are given by fixed thresholds that represent switching from location b to location a at some fixed high revenue spread level x_H and switching back from location a to b at some fixed low revenue level x_L. Due to the time homogenous property of value function (2) try a solution $\Phi(x_t) = e^{-\rho t}V(x_t)$. The dynamics of the value function (2) for location a and b should then satisfy the following equations in order for the controls to be optimal

$$-\rho V_a + (\widehat{\alpha} - x)V_a' + \frac{1}{2}\sigma^2 V_a'' + x - c_a = 0 \tag{5}$$

$$-\rho V_b + (\widehat{\alpha} - x)V_b' + \frac{1}{2}\sigma^2 V_b'' = 0 \tag{6}$$

Eq. (5) implies that the instantaneous return on the value of keeping the unit in location a, and optimally utilising the options to move between locations in the future, is given by the change in the value due to the change in the revenue spread X_t, i.e., from the change in the excess revenue from operating in location a instead of b, plus the instantaneous cashflow spread. Eq. (6) implies that the instantaneous return on the value of keeping the unit in location b, and optimally utilising the options to move between locations in the future, is equal to the change in the value due to the change in the revenue spread X_t.

A higher value of X_t has a positive effect on the value of operating in location b due to the positive effect on the real options to switch locations in the future. Given that we only study the value effect of the cash-flow spread dynamics of location a, i.e., there is by definition no such cash-flow in location b, the value function $V_{b,\ t}$ purely represents the option value at time t of optimally changing locations in the future. The value function in location b, dependent on the excess cash-flow in location a, is given by

$$V_b(x) = A_b\left(\begin{array}{c} M\left(\frac{\rho}{2\kappa}, \frac{1}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - x)^2\right) \\ -\frac{\sqrt{\kappa}}{\sigma}(\widehat{\alpha} - x)\frac{\Gamma\left(\frac{1}{2}\right)\Gamma\left(\frac{\rho+\kappa}{2\kappa}\right)}{\Gamma\left(\frac{3}{2}\right)\Gamma\left(\frac{\rho}{2\kappa}\right)}M\left(\frac{(\kappa+\rho)}{2\kappa}, \frac{3}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - x)^2\right) \end{array}\right) \tag{7}$$

where $M(\bullet)$ is Kummer's (confluent hypergeometric) function, $\Gamma(\bullet)$ is the gamma function and A_b is a constant.

The value function in location a is given by the option values of switching locations, equivalent to the values of the switching options in location b (7), plus the value of the cashflow in the case of an infinite deployment of the unit in location a, i.e.,

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[2] https://www.domstol.no/en/enkelt-domstol/supremecourt/rulings/2021/supreme-court—civil-cases/hr-2021-1975-s/.

$$V_a(x) = A_a \left(\begin{array}{c} M\left(\frac{\rho}{2\kappa}, \frac{1}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - x)^2\right) \\ + \frac{\sqrt{\kappa}}{\sigma}(\widehat{\alpha} - x)\frac{\Gamma\left(\frac{1}{2}\right)\Gamma\left(\frac{\rho+\kappa}{2\kappa}\right)}{\Gamma\left(\frac{3}{2}\right)\Gamma\left(\frac{\rho}{2\kappa}\right)} M\left(\frac{\kappa+\rho}{2\kappa}, \frac{3}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - x)^2\right) \end{array} \right) + \frac{x - \widehat{\alpha}}{\rho + \kappa} + \frac{\widehat{\alpha} - c_a}{\rho} \tag{8}$$

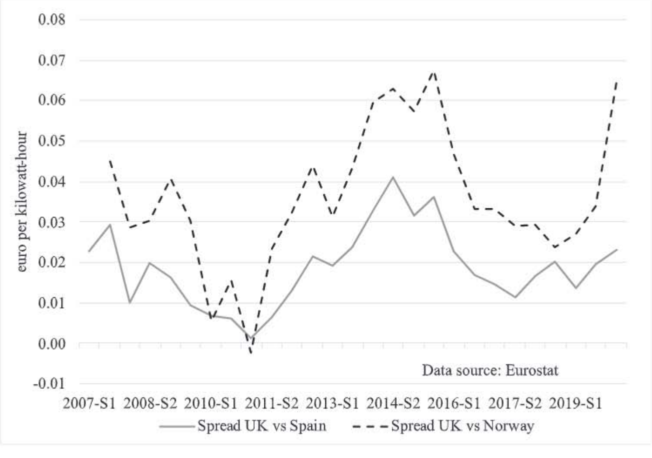
where A_a is a constant. See the appendix for more on deriving relations (7) and (8).

Let the optimal threshold for leaving location b and entering location a be given by $x^{b \to a}$ and the optimal threshold for leaving location a and entering location b be given by $x^{a \to b}$. These optimal entry and exit levels must satisfy a set of value matching and smooth pasting conditions. See Dixit (1993). That is, $V_b(x^{b \to a}) = V_a(x^{b \to a}) - K^{b \to a}$, $V_a(x^{a \to b}) = V_b(x^{a \to b}) - K^{a \to b}$, $V_b'(x^{b \to a}) = V_a'(x^{b \to a})$ and $V_a'(x^{a \to b}) = V_b'(x^{a \to b})$. These conditions determine the constants A_a and A_b and the optimal trigger values $x^{b \to a}$ and $x^{a \to b}$. The values $V_a(x)$ and $V_b(x)$ then give the extra value of mobility, in location a or location b respectively, relative to being permanently deployed in location b. That is, the values $V_a(x)$ and $V_b(x)$ represent the extra value of a floating mobile offshore wind unit, in location a and b respectively, relative to a fixed-bottom offshore wind unit in location b. In location b the value will be zero or positive given that the choice not to move, and thereby replicating the lack of mobility of the fixed-bottom unit, is always an option. The value may, however, be negative in location a, because high moving costs may make it optimal to continue running at a loss in location a relative to the profit of a fixed-bottom unit in location b.

4. Floating offshore wind valuation and optimal relocation strategies - numerical illustrations

Large scale floating offshore wind parks are yet to be commissioned. Data is limited. The following examples are partly based on input from informants close to the industry and partly on data from European electricity markets. The simulations illustrate the potential for real options valuation in floating offshore wind – but they are not case studies.

European electricity prices are usually correlated due to common demand and production costs factors like shared business cycles, seasons and weather conditions, international markets for coal, oil and gas and partly integrated European electricity markets via border crossing electricity cables. However, there is still substantial volatility in the spreads between the electricity prices of many European countries. Fig. 1 shows the spreads between UK and Spanish and UK and Norwegian electricity prices in KWh for non-household consumers before taxes. The semi-annual observations, starting in 2007, are from Eurostat.



Data source: Eurostat

Fig. 1. Electricity price spreads for non-household consumers - semi-annual observations.

To establish a base case, assumptions and parameter values are as follows: the electricity price spread between market a and b follows the Ornstein-Uhlenbeck process Eq. (1). The long-run average electricity price in the two markets are identical. That is, the parameter α of Eq. (1) is zero. Mean reversion, i.e., parameter κ of Eq. (1), is 1. The volatility of the spread in the electricity price between market a and b is EUR 35MWh.

Let the unit's turbine capacity be 10 MW and let production run 24 h a day and 365 days a year at an average capacity factor of 50%.[3] The average capacity factor reflects average wind conditions, maintenance and potential production disruptions. Given these base case assumptions the volatility of the 10 MW turbine's annual cashflow spread in location a vs location b, i.e., σ of Eq. (1), is approximately EUR 1.500.000.[4]

Cost-efficient docking technologies are yet to be developed that can make relocation of a floating offshore wind unit attractive under reasonable market volatility. Therefore, the cost of moving a unit from location b to a, in a future efficient market, must be based on stipulations. Assume that it takes 30 days to relocate one unit from location b to a. If the electricity price is EUR 50MWh, then the loss of revenue due to the relocation is EUR 180.000. In addition to the pure revenue loss, there will be costs related to the physical relocation of the unit. As a base case let both $K^{b \to a}$ and $K^{a \to b}$ be EUR 360.000. That is, the cost of relocation is set at two times the revenue loss.[5] This appear to be a reasonable scenario in the case that existing docking, mooring, transformer and grid connection infrastructure allows for easy hook-up at the new location. In a future mature floating offshore wind industry, a high value of relocation flexibility may allow for proactive investments in infrastructural redundancy. The effect of significantly higher relocation costs, which will characterise the early phases of the industry, is discussed below.

As a reference, assume that the value of a permanently located offshore wind unit in location b is given by the present value of an infinite horizon cashflow from a 10 MW installed capacity with a capacity factor of 50%. Let the base case discount factor, ρ, be 7.5% and the benchmark electricity price be EUR 50MWh. Given the base case parameter assumptions, the net present value of the future cashflow of a permanently located offshore wind unit, i.e., the value of a fixed-bottom 10 MW turbine in location b, is EUR 29.2 million.[6]

Table 1 shows the value of the flexibility to relocate and the optimal trigger levels in terms of the electricity price spreads between region a and b for different levels of volatility. The trigger levels are reported in euro per MWh.

In the base case, i.e., if σ is EUR 1.5 million, the value of the flexibility to relocate is EUR 2.92 million. This corresponds to 10% of the value of a fixed-bottom unit in location b. The value of the floating offshore wind unit, including option values, is EUR 31.12 million.

The optimal strategy if starting out in location b, i.e., the location of the fixed-bottom unit, is to move the floating unit to location a when the electricity price in location a is EUR 26.5MWh higher than in location b. Due to the symmetry in the base case parameter values there is also symmetry in the trigger price spread levels. That is, when the unit is

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[3] For Hywind Scotland the main owner Equinor reports an average capacity factor for the first two years of 54% and an even higher 57.1% in the twelve months to March 2021.

[4] EUR35MWh*10MWh*24 h*365 days*50% = EUR 1.533.000.

[5] The towing of one unit from Stord in Norway to the Hywind Scotland location took about 5 days using anchor handling tug supply vessels – a main tug and an assisting tug. The tow out and offshore cable installation took about two months according to Statoil's "Hywind Scotland Pilot Park Project Plan for Construction Activities 2017". The whole offshore installation campaign was carried out between April and August 2017.

[6] EUR50MWh*10MWh*24 h*365 days*50%:7.5% = EUR 29.200.000.

Table 1
Value of flexibility and relocation policy for different levels of volatility.

Value of σ in million €	*Value of flexibility in million €*	*Value of flexibility, % of fixed-bottom*	$x^{b\to a}$	$x^{a\to b}$
0.5	0.35	1.2%	14.3	−14.3
1.0	1.52	5.2%	20.9	−20.9
1.5	2.92	10.0%	26.5	−26.5
2.0	4.42	15.1%	31.6	−31.6
2.5	5.97	20.4%	36.3	−36.3
3.0	7.57	25.9%	40.7	−40.7
3.5	9.19	31.1%	44.9	−44.9
4.0	10.83	37.1%	48.9	−48.9
4.5	12.49	42.8%	52.7	−52.7
5.0	14.17	48.5%	56.4	−56.4

Trigger levels of the electricity price difference in the table are reported in MWh.

located in a then the optimal strategy is to move the unit back to location b when the electricity price in location a is EUR 26.5MWh lower than in location b.

In the low volatility case, i.e., if σ is EUR 500,000, the value of the option to relocate is only EUR 350,000. That is, the floating offshore wind unit is only 1.2% more valuable than a fixed-bottom unit. In the high volatility case, i.e., if σ is EUR 5 million, the value of the option to relocate is EUR 14.17 million, i.e., the floating offshore wind unit is 48.5% more valuable than the corresponding fixed-bottom unit. Observe that in the high volatility case the value of waiting is so paramount that the optimal strategy is to relocate only when the spread is EUR 56.4MWh. In the low volatility case, the optimal strategy is to relocate when the spread is EUR 14.3MWh.

Table 2 shows the value of the relocation options and the optimal relocation strategies for different levels of the mean reversion parameter κ. A high level of κ implies that the markets are strongly integrated and that the time that one market stays favourable relative to the other in most cases is short. A high mean reversion in the electricity price spread between market a and b, reduces the value of the flexibility to relocate.

In the base case the value of κ is 1 and the value of the flexibility to relocate is EUR 2.92 million, which is 10% of the value of a fixed-bottom unit. When the mean reversion parameter κ is at a low 0.25 then the value of flexibility increases to EUR 8.73 million, i.e., the value of flexibility is 29.9% of the value of a fixed-bottom unit. Very high mean reversion, i.e., the markets are strongly integrated, removes the value of the flexibility. For example, in the case that $\kappa = 3$ the value of flexibility is only 0.7% of the value of the fixed-bottom unit.

The actual cost of relocating a floating offshore wind unit in the future depends on the degree of technological progress towards developing efficient docking solutions. Another key issue is the reuse of mooring, transformer and grid connection infrastructure. At present infrastructure is location specific and typically represents one-third of total investment costs. To reduce costs is vital for increasing the value of relocation flexibility.

Table 2
Value of flexibility and relocation policy for different levels of mean reversion.

Value of κ	*Value of flexibility in million €*	*Value of flexibility, % of fixed-bottom*	$x^{b\to a}$	$x^{a\to b}$
0.25	8.73	29.9%	25.0	−25.0
0.50	5.57	19.1%	25.5	−25.5
0.75	3.95	13.5%	26.0	−26.0
1.00	2.92	10.0%	26.5	−26.5
1.25	2.18	7.5%	27.1	−27.1
1.50	1.64	5.6%	27.7	−27.7
1.75	1.22	4.2%	28.4	−28.4
2.00	0.90	3.1%	29.1	−29.1
2.25	0.65	2.2%	29.9	−29.9
2.50	0.45	1.5%	30.8	−30.8
2.75	0.31	1.1%	31.8	−31.8
3.00	0.20	0.7%	32.8	−32.8

Trigger levels of the electricity price difference in the table are reported in MWh.

Table 3
Value of flexibility and relocation policy for different relocation cost levels.

Relocation costs,000€ $K^{a\to b} = K^{b\to a}$	*Value of flexibility in million €*	*Value of flexibility, % of fixed-bottom*	$x^{b\to a}$	$x^{a\to b}$
0	5.52	18.9%	0	0
90	5.39	15.0%	15.9	−15.9
180	3.78	13.0%	20.4	−20.4
360	2.92	10.0%	26.5	−26.5
540	2.28	7.8%	31.3	−31.3
720	1.78	6.1%	35.5	−35.5
900	1.39	4.7%	39.3	−39.3
1080	1.07	3.6%	42.9	−42.9
1260	0.81	2.8%	46.5	−46.5
1440	0.60	2.1%	49.9	−49.9
1620	0.44	1.5%	53.4	−53.4

Trigger levels of the electricity price difference in the table are reported in MWh.

Table 3 shows the real option values and the optimal relocation strategies for different levels of the relocation costs $K^{a\to b}$ and $K^{b\to a}$. $K^{a\to b}$ and $K^{b\to a}$ are assumed to be symmetric. In the base case, i.e., a one-way relocation cost of EUR 360,000, the value of the relocation flexibility is, as discussed above, 10% of the value of the fixed-bottom unit. Theoretically, if there is no cost of relocation, then the value of the real options to relocate is as high as 18.9% of the value of the fixed-bottom unit. The optimal strategy in the case of no relocation costs is to move immediately as the price in one region deviates only marginally from the other. That is, $x^{a\to b}$and $x^{b\to a}$ are both zero. This result is only of interest from a model technical point of view. Relocation costs will always be significant. For a high relocation cost the value of the real options to relocate is low. Given the base case parameter values and relocation costs $K^{a\to b}$ and $K^{b\to a}$ at EUR 1.62 million the value of the flexibility to relocate is only 1.5% of the value of the fixed-bottom unit. The trigger values are as high as EUR 53.4MWh.

The model allows for higher or lower long run average electricity prices in region a than in region b. That is, the long run average electricity spread parameter α may take positive or negative values. Table 4 shows the effect of different levels of α given unchanged base case values for the other parameters. A negative level of α implies that the long run average of the electricity price in location a is lower than in location b. The value of the flexibility to move from b to a is reduced and the optimal trigger value $x^{b\to a}$ becomes higher. The value of moving from a to b and the optimal trigger value $x^{a\to b}$ becomes less negative.

The model allows for differences in the cost structure of deploying the unit in location a vs location b. That is, c_a may take positive or negative values. The effect of changes in relative cost advantages is discussed in the next section.

The model also allows for different levels of the discount factor ρ. Changes in the discount factor have strong effects on the value of

Table 4
Value of flexibility and relocation policy for different mean spread levels.

Mean spread, α,000€	*Value of flexibility in million €*	*Value of flexibility, % of fixed-bottom*	$x^{b\to a}$	$x^{a\to b}$
−300	1.46	5.0%	30.0	−23.3
−250	1.65	5.7%	29.4	−23.8
−200	1.87	6.4%	28.8	−24.4
−150	2.10	7.2%	28.2	−24.9
−100	2.35	8.1%	27.7	−25.4
−50	2.62	9.0%	27.1	−26.0
0	2.92	10.0%	26.5	−26.5
50	3.23	11.1%	26.0	−27.1
100	3.56	12.2%	25.4	−27.7
150	3.92	13.4%	24.9	−28.3
200	4.29	14.7%	24.4	−28.8
250	4.69	16.0%	23.8	−29.4
300	5.10	17.5%	23.3	−30.0

Trigger levels of the electricity price difference in the table are reported in MWh.

flexibility. For example, the value of the option to relocate decreases from EUR 2.92 million in the base case to EUR 1.36 million if the discount rate increases from 7.5% to 15%. However, the change in valuation is almost entirely due to standard discount factor effects. Relative to the net present value of the cashflow of the fixed-bottom unit in location *b,* the value of flexibility only declines from 10% to 9.3%. The optimal relocation strategies are hardly affected. The trigger values only increase from EUR 26.53MWh to EUR 26.83MWh. That is, optimal strategies are robust to changes in discount factors.

All tables so far have been for the risk neutral case. Fig. 2 shows the entry and exit thresholds for different levels of the volatility parameter σ, for a risk neutral agent and for a risk averse agent. The market price of risk is set at $\lambda = 0.15$. This implies that $\widehat{\alpha}$ in Eq. (4) is minus EUR 22.500. That is, the long run certainty equivalent expected cashflow in region a is negative. The effect on the entry and exit thresholds are straight forward. Both levels are higher than in the risk neutral case. That is, risk aversion implies that the floating unit will be moved to location a later and moved back to location b sooner.

5. Model extension – three offshore wind locations and two markets

In the model above the floating offshore wind unit can be deployed at two different locations that supply two different partly integrated markets. It is reasonable to assume that during the lifetime of a floating offshore wind unit the number of feasible locations may be higher than two. In this section a third production location is added, i.e., there are two partly integrated markets and three potential production locations.

The floating offshore wind unit is initially deployed in location b. The unit may be relocated to location a. A third location c is also available. Let the cost of moving the unit from location a to c, $K^{a\rightarrow c}$, be lower or equal to the cost of moving the unit from location a to b, i.e. $K^{a\rightarrow c} \leq K^{a\rightarrow b}$. Location c supplies electricity to the same market as location *b, market 1.* As above location a supply electricity to a separate market, *market 2.* The extra revenue earned in location a vs location b is assumed to be identical to the extra revenue earned in location a vs location c. That is, in both cases the spread is given by process (1).

Let there be an operation cost advantage in location c relative to location b given by a negative number, c_c. However, let it be optimal to remain in location b instead of moving to location c in light of high costs of relocation. The owner's initial option is therefore either to stay in location b or to move to location a – as above. Formally, $V_c(x) - K^{b\rightarrow c} < V_b(x)$ for all $x < x^{b\rightarrow a}$. However, if the unit is moved to location a, then the real option to move to location c is always more valuable, due to the cost structure, than the option to return to location b.

In the alternative case of very low relative operation costs in location c and moderate switching costs between b and c, the value matching and smooth pasting conditions for an optimal relocation from b to c may be reached before an optimal relocation from b to a is reached. In this case the initial move will be from location b to c. Formally, $V_c(x^{b\rightarrow c}) - K^{b\rightarrow c} = V_b(x^{b\rightarrow c})$ and $V_c{}'\left(x^{b\rightarrow c}\right) = V_b{}'\left(x^{b\rightarrow c}\right)$ for some $x^{b\rightarrow c} < x^{b\rightarrow a}$, where $x^{b\rightarrow c}$ is the optimal threshold for leaving location b and entering location c. In this case the unit will never be moved from b to a. The option to move from b to a will be without any value or effect on relocation thresholds. This case is not developed any further here.

Fig. 3 illustrates a potential scenario in line with the model's assumptions. The floating offshore wind unit is initially deployed in the North Sea, *location b,* and supplies electricity to the UK market, *market 1.* At some point in time the real option to relocate to the Bay of Biscay, *location a,* is exercised and the unit starts supplying electricity to the Spanish market, *market 2.* If the unit is located in the Bay of Biscay the unit may in the future switch between supplying electricity to the UK and Spanish markets by switching locations. However, the next potential move will be a relocation from the Bay of Biscay to the Irish Sea, *location c,* and not back to the North Sea, due to assumed lower relocation and production costs in the Irish Sea than to the North Sea.

The value function in the case that the unit is located in b is given by (7) above. The value function in the case that the unit is located in a is similar in structure to (8) above. However, if the unit is located in a the next potential move is from a to c, not from a to b. All future moves will be between a an c given that a move back to location b will always be an inferior strategy compared to remaining in location c or moving from location a to location c. The constant A_a is therefore dependent on the characteristics of locations a and c and not on the characteristics of location b.

$$V_a(x) = A_a\left(\begin{array}{c} M\left(\frac{\rho}{2\kappa}, \frac{1}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - x)^2\right) \\ + \frac{\sqrt{\kappa}}{\sigma}(\widehat{\alpha} - x)\frac{\Gamma\left(\frac{1}{2}\right)\Gamma\left(\frac{\rho+\kappa}{2\kappa}\right)}{\Gamma\left(\frac{3}{2}\right)\Gamma\left(\frac{\rho}{2\kappa}\right)}M\left(\frac{\kappa+\rho}{2\kappa}, \frac{3}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - x)^2\right)\end{array}\right) + \frac{x - \widehat{\alpha}}{\rho + \kappa} + \frac{\widehat{\alpha} - c_a}{\rho} \tag{9}$$

The value function in the case that the unit is located in c is similar in structure to (7) – only adjusted for the cost advantage of location c over

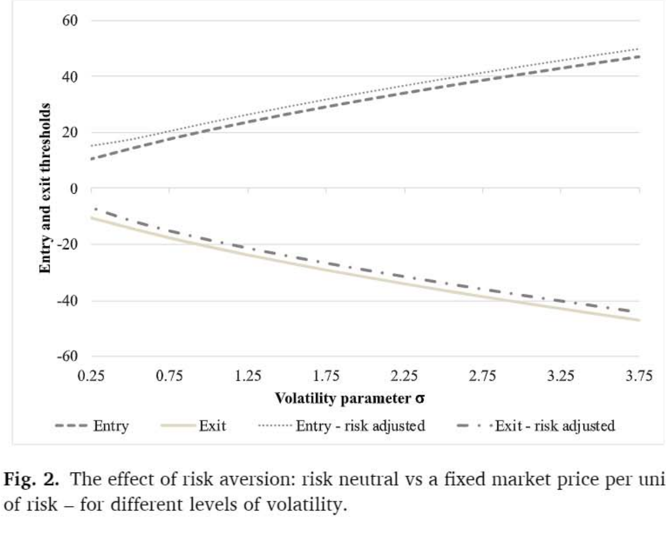

Fig. 2. The effect of risk aversion: risk neutral vs a fixed market price per unit of risk – for different levels of volatility.

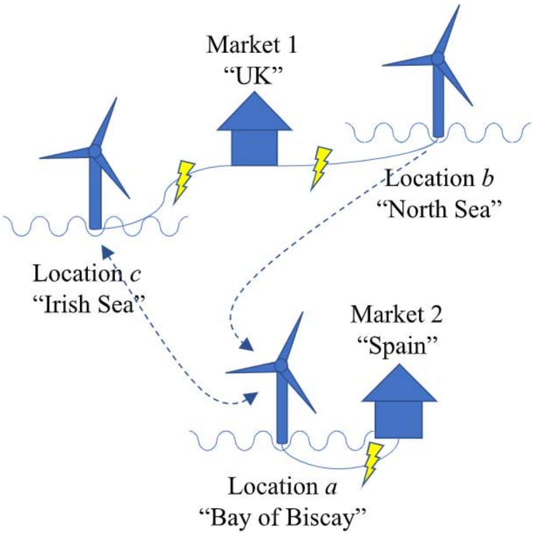

Fig. 3. A scenario of relocating a floating offshore unit between three locations and two markets.

location *b*, c_c. That is,

$$V_c(x)=A_c\left(\begin{array}{c}M\left(\frac{\rho}{2\kappa},\frac{1}{2},\frac{\kappa}{\sigma^2}(\widehat{\alpha}-x)^2\right)\\ -\frac{\sqrt{\kappa}}{\sigma}(\widehat{\alpha}-x)\frac{\Gamma\left(\frac{1}{2}\right)\Gamma\left(\frac{\rho+\kappa}{2\kappa}\right)}{\Gamma\left(\frac{3}{2}\right)\Gamma\left(\frac{\rho}{2\kappa}\right)}M\left(\frac{(\kappa+\rho)}{2\kappa},\frac{3}{2},\frac{\kappa}{\sigma^2}(\widehat{\alpha}-x)^2\right)\end{array}\right) -\frac{c_c}{\rho} \tag{10}$$

where A_c is a constant that is given by border conditions.

As above let the optimal threshold for leaving location *b* and entering location *a* be $x^{b\to a}$. Let the optimal threshold for leaving location *a* and entering location *c* be $x^{a\to c}$. Let the optimal threshold for leaving location *c* and entering location *a* be $x^{c\to a}$.

The optimal entry- and exit levels must satisfy the following set of value matching and smooth pasting conditions: $V_b(x^{b\to a}) = V_a(x^{b\to a}) - K^{b\to a}$, $V_a(x^{a\to c}) = V_c(x^{a\to c}) - K^{a\to c}$, $V_c(x^{c\to a}) = V_a(x^{c\to a}) - K^{c\to a}$, $V_b{}'(x^{b\to a}) = V_a{}'(x^{b\to a})$, $V_a{}'(x^{a\to c}) = V_c{}'(x^{a\to c})$, and $V_c{}'(x^{c\to a}) = V_a{}'(x^{c\to a})$. The constants A_a, A_b and A_c and the optimal trigger values $x^{b\to a}$, $x^{a\to c}$ and $x^{c\to a}$ can be derived from these conditions. Technically, the values A_a and A_c and $x^{a\to c}$ and $x^{c\to a}$ may be estimated separately, in the same way as in the above model. This follows since the optimal strategies of switching between *a* and *c* are not affected by the initial move from location *b* to *a*. The constant A_b and the optimal trigger $x^{b\to a}$ may be estimated from the remaining value matching and smooth pasting conditions – given the estimated value of A_a.

The optimal relocation strategy from location *b* to *a* will be affected, not only by characteristic of these locations, but also by characteristics of location *c*. By relocating from *b* to *a* the real options to move from location *b* is lost and the real options to switch between location *a* and other locations are gained. Given the assumed cost advantage of location *c* over *b*, the new relevant real options that are gained by leaving location *b* are future switches between location *a* and *c*.

Fig. 4 shows the optimal thresholds for switching from locations *b* to *a* and from location *c* to *a* for different level of the production cost advantage of location *c*, c_c. All other parameter values are as in the base case. Except for the production cost advantage c_c, location *c* is identical to location *b*. The optimal threshold for leaving location *a* for location *c* is lower for a higher cost advantage. The optimal threshold for leaving location *b* for location *a* is also lower. That is, it becomes more attractive to leave location *b* and entering location *a,* and thereby gaining the options to relocate between locations *a* and *c* later, if the cost advantage of location *c* increases.

A reduction in the costs of moving the unit between locations *a* to *c*, i.e., a parallel reduction in both $K^{a\to c}$ and $K^{c\to a}$, reduces the optimal threshold of moving from *c* to *a* and increases the optimal threshold from moving from *a* to *c*. For base case values the effects are as in Table 3 above.

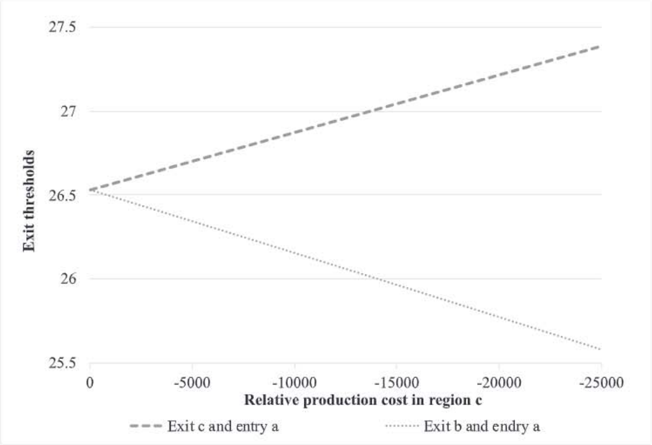

Fig. 4. The effect of reduced production cost at location c on the real options thresholds to switch to location a – from either location b or c.

The lower costs of moving between location *a* and *c* make the real options to relocate from location *b* more attractive. Fig. 5 shows the threshold for moving from *c* to *a*, $x^{c\to a}$,and from *b* to *a, $x^{b\to a}$*. The costs of moving the unit away from location *b* to location *a* or *c* are assumed to be fixed at the benchmark level. Lower switching costs between location *a* and *c* reduce the threshold for moving from *b* to *a*. This follows since, in order to enjoy the lower switching costs between *a* and *c* in the future the owner first has to trigger a moved from *b* to *a*. The effect on the optimal threshold $x^{b\to a}$ is significant but smaller than the effect on $x^{c\to a}$.

6. Model limitations and potential extensions[7]

The model is a first pass at evaluating relocation flexibility in floating offshore wind. A possible next step is to incorporate alternative specifications of uncertainty. As renewable energy becomes a larger part of the total energy mix, electricity prices may become more correlated with generation of renewable energy, e.g., electricity prices may become high when weather conditions for solar and wind are unfavourable and vice versa. A negative correlation between price and production may dampen the value of relocation options.

For applications a more detailed specification of the relocation process could be useful. The current mathematical model assumes instantaneous relocation, which is analytically convenient. However, relocation takes time. Relocation involves hazards – including the risk of structural fatigue. Relocation costs and market conditions at the new location may only be partly known when relocation is initiated.

Relocation costs, that today can be prohibitively high, may decline going forward. The prospect of reduced relocation costs in the future positively affect the value of proactive investments in relocation flexibility today.

The model is estimated on European data up until the outbreak of the Covid-19 pandemic and the Ukraine conflict. A possible extension is to incorporate environmental and political shocks. High volatility and large regional differences in energy prices, triggered by unexpected events, add to the values of relocation flexibility.

The 2022 gas and electricity markets turmoil may spur more

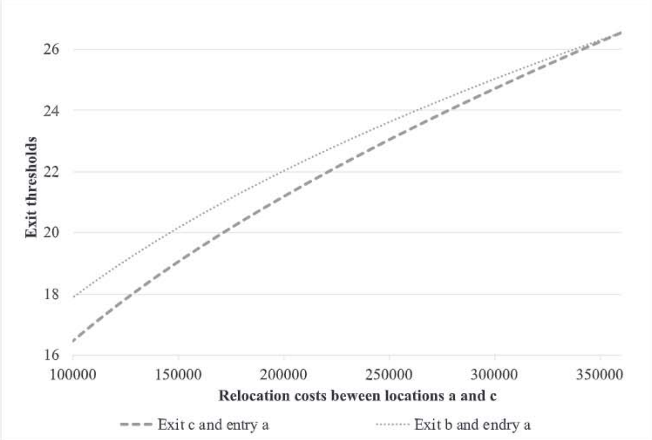

Fig. 5. The effect of reduced relocation costs between locations a and c on the real options thresholds to switch to location a – from either location b or c.

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[7] This section is partly inspired by ideas and suggestions from the anonymous referees.

investments in the integration of the European electricity markets. This may lower regional electricity price differences and, consequently, the value of relocation flexibility may be reduced. However, the disruption to gas export from Russian and the sabotage of the Baltic Sea Nord Stream 1 and 2 pipelines may contribute to undermine the perceived reliability of fixed installations and increase the awareness of the strategic value of flexibility – including relocation optionality. The papers' framework may be useful for analysing such issues, e.g., the relocation of floating storage and regasification units (FSRU) to Germany during 2022 to allow for import of gas via LNG tankers from alternative and distant sources.

7. Concluding comments

The floating offshore wind industry is technologically and commercially in an early phase. The flexibility to relocate physical units is a unique characteristic that separates the floating offshore wind industry from most traditional electricity generating industries and the fixed-bottom offshore wind industry. Conditions are favourable for relocation in the case of high volatility and low mean reversion in relative cashflows between locations or markets. Uncertainty related to institutional factors like subsidy regimes, tax policies, political uncertainty, collateral valuation and environmental factors may create relocation opportunities during the lifespan of a floating offshore wind unit.

At present the LCOE of a floating offshore wind unit is high due to untested technology, lack of large-scale floater fabrication and small-scale wind farms. Technological progress, standardisation and large-scale fabrication may lower the cost of floating relative to fixed-bottom units. This study indicates that optimal relocation strategies may contribute to the relative competitiveness of the floating offshore wind industry.

In the early phase of the industry, high switching costs will limit relocation of floating offshore wind units. In a mature industry, proactive investments in redundancy in docking, mooring, transformer and grid connections may allow for low-cost relocation of units inside a portfolio of locations and markets. The value of relocation flexibility may be high enough to make infrastructural redundancy investments attractive. Relocation as a tool for maximising the value of a portfolio of floating offshore wind farms may be an interesting field for future research.

The strategic complexity of switching between production locations and regional electricity markets in a future global floating offshore wind industry may become high. This study contributes to establishing a framework for evaluating these real options.

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Appendix

Sødal et al. (2008) provide a mathematical solution to relation (2) in the risk neutral case. The general solution to the value function for location b, i.e., the solution to the homogenous partial Eq. (2), is given by

$$V_b(x) = A_b M\left(\frac{\rho}{2\kappa}, \frac{1}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha}-x)^2\right) + B_b(\widehat{\alpha}-x) M\left(\frac{(\kappa+\rho)}{2\kappa}, \frac{3}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha}-x)^2\right) \tag{1a}$$

where $M(\bullet)$ is Kummer's (confluent hypergeometric) function and A_b and B_b are constants.

The solution to the value function in location a is given by the general solution to the homogenous part and a particular solution to the inhomogenous part of Eq. (5). A particular solution follows from the pure net present value of the future excess cashflows in location a under the certainty equivalent probability measure, i.e.,

$$E^Q\left[\int_0^\infty e^{-\rho s}(x_s - c_a)ds\right]_{x0=x} = \frac{x-\widehat{\alpha}}{\rho+\kappa} + \frac{\widehat{\alpha}-c_a}{\rho} \tag{2a}$$

Relation (2a) is the solution to (2) in the case that no control is exercised now or in the future, i.e., there is no future switching between the locations. The solution to (2) when operating in location a is then

$$V_a(x) = A_a M\left(\frac{\rho}{2\kappa}, \frac{1}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha}-x)^2\right) + B_a(\widehat{\alpha}-x) M\left(\frac{(\kappa+\rho)}{2\kappa}, \frac{3}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha}-x)^2\right) + \frac{x-\widehat{\alpha}}{\rho+\kappa} + \frac{\widehat{\alpha}-c_a}{\rho} \tag{3a}$$

As argued by Sødal et al. a reasonable optimality requirement is that the value of the real option to move from location b to location a should approach zero as the excess return of operating in location a approaches very negative numbers. That is, $\mathrm{V}_{b,\,t} \rightarrow 0$ as $x \rightarrow -\infty$. In the same way, the real option to move from location a to location b should approach zero if the excess return of operating in location a approaches very high numbers. That is, $\mathrm{V}_{a,\,t} \rightarrow 0$ as $x \rightarrow \infty$. Due to the asymptotic behaviour of Kummer's function, $\underset{z\rightarrow\infty}{lim} M(a,b,z) = \frac{\Gamma(b)}{\Gamma(a)} e^z z^{a-b}$, where $\Gamma(\bullet)$ is the gamma function, it follows that the value function in location b, dependent on the excess cash-flow in location a, is given by

$$V_b(x) = A_b \left(\begin{array}{c} M\left(\frac{\rho}{2\kappa}, \frac{1}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha}-x)^2\right) \\ -\frac{\sqrt{\kappa}}{\sigma}(\widehat{\alpha}-x)\frac{\Gamma\left(\frac{1}{2}\right)\Gamma\left(\frac{\rho+\kappa}{2\kappa}\right)}{\Gamma\left(\frac{3}{2}\right)\Gamma\left(\frac{\rho}{2\kappa}\right)} M\left(\frac{(\kappa+\rho)}{2\kappa}, \frac{3}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha}-x)^2\right) \end{array}\right) \tag{4a}$$

The value function in location a, dependent on the excess cash-flow in location a, is given by

$$V_a(x) = A_a \left(\begin{array}{c} M\left(\frac{\rho}{2\kappa}, \frac{1}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - x)^2\right) \\ + \frac{\sqrt{\kappa}}{\sigma}(\widehat{\alpha} - x) \frac{\Gamma\left(\frac{1}{2}\right)\Gamma\left(\frac{\rho+\kappa}{2\kappa}\right)}{\Gamma\left(\frac{3}{2}\right)\Gamma\left(\frac{\rho}{2\kappa}\right)} M\left(\frac{\kappa+\rho}{2\kappa}, \frac{3}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - x)^2\right) \end{array} \right) + \frac{x - \widehat{\alpha}}{\rho + \kappa} + \frac{\widehat{\alpha} - c_a}{\rho} \tag{5a}$$

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