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The Importance of Learning for Achieving the UK's Targets for Offshore Wind☆

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ABSTRACT

Using a purpose-built, multi-sectoral energy-economy-environmental model we evaluate the economic and environmental impact of a reduction in the levelized costs of offshore wind energy generation in the UK. Our modelling approach suggests that in order to significantly increase the offshore wind capacity in the UK the required fall in the generation cost should be larger than expected and certainly bigger than that implied by the most recent cost projections developed by the UK Department of Energy and Climate Change (DECC). Potential expansion of the offshore wind sector in the UK crucially depends on the price sensitivity of the energy supply sector and on agent's expectations. Only in our more optimistic scenario do we reach DECC's ambitious challenge of 22 GW offshore wind deployment in 2030 through a constant learning rate alone.

1. Introduction

The expectation that offshore wind costs will fall as the technology is deployed is based on the concept of "learning-by-doing" (Arrow, 1962). Learning or experience curves represent a well-documented relationship between experience gains and costs reductions in a range of industries (Argote and Epple, 1990). The learning rate is the proportionate cost reduction associated with every doubling of experience (for a given technology). A number of studies have estimated the learning rates associated with both renewable and conventional energy technologies. (for good reviews, see McDonald and Schrattenholzer, 2001 and Kahouli-Brahmi, 2008; for a meta-analysis of wind power learning rates see Lindman and Söderholm, 2012). The renewable technologies onshore wind and photovoltaic energy, have experienced learning rates as high as 35% (IEA, 2000), and an average of 11% and 20% respectively.

Offshore wind energy, as a relatively new technology, has not yet experienced these large cost reductions, despite early expectations that its development would closely follow the path of onshore wind technology (DTI, 2002; Junginger et al., 2005). Rather, the costs of offshore wind have experienced a rise in the mid-2000s, due to a range of factors such as the increasing depth and distance to shore, lack of competition in component production, bottlenecks in the supply chain, and increases in commodity prices (UK Energy Research Centre (UKERC), 2010).

Nevertheless, there is a consensus that significant learning opportunities are achievable in offshore wind energy in the coming decades, particularly in the UK where further benefits are expected to occur through investments in a domestic supply chain (UKERC, 2010; Pan and Köhler, 2007).

The Offshore Wind Costs Reduction Taskforce's report (OWCRT, 2012) concluded that the government's target levelised costs of £100/MWh for offshore wind in 2020 is challenging but achievable. Based on this report, as well as results from industry consultation, the Electricity Market Reform Delivery Plan modelling exercise assumes a deployment-based learning rate of 12% and the £100/MWh target to be delayed by three years (reached in 2023), reflecting the uncertainty surrounding the evolution of levelised costs (Department of Energy and Climate Change, 2013b).

In this paper, we attempt systematically to investigate the economic and environmental impact of a reduction in the levelized costs of offshore wind energy generation as projected by DECC, using an energy-disaggregated computable general equilibrium model of the UK. Compared to DECC's own analysis, we allow for the full system-wide interactions of the energy, economy and environment sub-systems. We investigate under what conditions DECC's 2030 capacity targets for offshore wind electricity generation are attainable when driven solely by the assumed cost reductions generated by learning. Both aggregate

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and sectoral economic activities are endogenous to the model, but we focus exclusively on the impact of the assumed technological change.

DECC's approach is based on an electricity demand model (see for instance DECC, 2012), where the interaction between sub-systems is determined by a fixed relationship, which is therefore unable to capture the more complex system-wide impact of a cost reduction through technological changes. Our modelling approach, however, explores the likely change by fully incorporating the energy-economy-environment interactions that are not typically accommodated in the kinds of models that DECC employs to inform its projections. We can track the impact of the change on both aggregate and sectoral economic activity (and employment levels) and on the level of emissions. Furthermore, price sensitivity is incorporated endogenously into the model and allows changes in energy inputs, reflecting substitution possibilities, which in turn generate a shift in technologies thereby producing the optimal electricity mix as a result of the impacts of the learning rate. For example, higher substitution between energy technologies increases the substitution away from fossil-fuel sectors towards offshore wind that has the effect of increasing capacity in this sector and potentially generating a significant reduction in total CO2 emissions.

Furthermore, we investigate the possibility of curbing emissions while simultaneously achieving economic growth through expansion in offshore wind. We also explore the implications that different agents' dynamic behaviours have in achieving the offshore wind capacity target. We are able to show that economic transition under myopic or adaptive expectations is very different from that under perfect foresight. This is important for the effective early adoption of offshore wind since forward-looking behaviour requires confidence about the future.

We should emphasise that CGE models in general, and the UKENVI model in particular, are not designed to capture the detailed technical characteristics of particular energy generation or distribution technologies. The aim of the paper, as stated in the title, is to understand whether a reduction in the levelized cost of offshore wind energy -modelled through a change in productivity in this sector - could bring about an output expansion in that same sector. We also investigate under what conditions the expansion is consistent with DECC targets, when driven solely by improvements in generation efficiency. We also consider the probable energy mix that would result from changes in the agents' economic behaviour. We do not wish to evaluate the detailed technical issues that arise in reaching the offshore wind target. On the contrary we position our results as additional and complementary to DECC's findings.

We are conscious that for experiments aiming to evaluate the technical feasibility of an offshore wind project or to estimate the likely physical expansion of offshore wind energy, a fully integrated power market model such as the DECC Dynamic Dispatch Model (DECC, 2012) or an energy system model is required. Models such as MARKAL-TIMES (Kannan et al., 2008) or MESSAGE (Messner and Schrattenholzer, 2000) would probably be more appropriate to verify the technical feasibility of the future development of the energy systems. Our modelling approach instead tries to investigate the sectoral and aggregate behaviour that is reflected in the economy-wide responses to a particular policy. A hybrid approach that incorporates some elements of bottom-up and top-down models is probably more suitable and able to deliver insights that pure bottom-up models cannot (Strachan and Kannan, 2008). However, we also recognise the difficulties of incorporating in a single modelling framework the complexities and technical detail typically embodied in energy systems and CGE models. Prior to the development of such integrated models, we regard our CGE approach as complementary to energy systems models.

Section 2 is a brief account of the current and projected future deployment of offshore wind turbines in the UK. Section 3 provides a brief summary of the intertemporal UK energy-economy-environment computable general equilibrium model (CGE), UKENVI. Section 4 describes the dataset, parameterisation and calibration of the model and Section 5 discusses model simulations and results. Section 6 comprises brief conclusions.

2. Background

Since 2002, UK renewable generation has been incentivised through the Renewable Obligation (RO) system, through which generators of renewable electricity receive a certificate for each unit provided to the grid[1]. The banding of the RO system in 2009 recognised the differences in technological advancements among renewables. Offshore wind was classified as one of the favoured renewable technologies and received increased public support in recognition of its early stage of development and higher costs. Offshore wind electricity generators currently receive two Renewable Obligation Certificates per generated MWh, whereas onshore generators receive one (DECC, 2013d).

The UK's budget 2016 ensures new "contracts for difference" (CfD) funding allocated around £700 million to support offshore wind projects However, it seems there is still uncertainty over CfD offshore wind subsidies and indeed the support for onshore wind developments looks set to be withdrawn. CfDs will guarantee a stable sale price for renewable electricity generation, reducing uncertainty around the market price. Like the RO system, the "strike" price guaranteed in the contracts is technology-specific, depending on the stage of each technology's development, levelised costs and potential for cost reductions.

However, the competitiveness gap between renewables and traditional generation (and among renewables themselves) is expected to gradually close, as learning effects generate reductions in their levelised costs. Accordingly, the differentiated levels of support are expected to decrease in line with technology diffusion, ultimately moving towards a technology-neutral system (DECC, 2014).

In recent years, the UK offshore wind energy sector has experienced rapid development compared to other countries in Europe and the Rest of the World. Kota et al. (2015) provides a comparative analysis. A strong interest in renewable energy in general, and offshore wind in particular, was cultivated through a range of policy mechanisms. These included: strong political commitment to reduce carbon emissions; the replacement of the Non-Fossil Fuel Obligation scheme (NFFO) with the RO Certificates and the adoption of Cfd that reduce price uncertainties to industries and lasting support through a better defined subsidy scheme to promote long-term investments. In December 2013, the sector accounted for 3.7 GW of operational installed capacity, representing a five-fold increase from 2008 levels (DECC, 2013a), placing the UK as a global leader in offshore wind energy. Around 5% of UK electricity is currently generated by offshore wind, so that the UK generates more electricity from offshore wind than any other country in the world. With the abundance and availability of the offshore wind resource in the UK, the technology is expected to play a large part in the decarbonisation of the energy system, in order to reach the longer term target of 80% CO2 emission reductions (from 1990 levels) by 2050. Additionally, the UK government consider the expansion of the offshore wind energy sector as an opportunity to develop a competitive, UK-based supply chain, which could bring larger macroeconomic benefits in terms of employment and growth (HM Government, 2013).

Accordingly, the government's projections for the further deployment of offshore wind farms are ambitious. The most recent modelling exercises project more than a doubling of existing capacity by the end of the decade (10 GW in 2020, within an 8–15 GW range (DECC, 2013b)). Furthermore, the longer-term scenarios anticipate continued investments throughout the 2020s, with installed capacity reaching approximately 22GW by 2030 (and up to 41GW in the most optimistic scenario). While these projections are based on a number of assumptions about the electricity system (such as future policy decisions,

[1] With the sale of the certificates to suppliers, the RO system effectively acts as a subsidy to renewable generators, who receive a premium on the wholesale electricity price.

demand projections and carbon and fossil-fuel price projections), their crucial determinant is the evolution of offshore wind costs.

Currently, the major obstacle to the further deployment of offshore wind is the relatively high costs of the technology, which, like other renewable technologies, remains largely uncompetitive compared to conventional electricity generation[2]. In terms of levelised costs of energy, offshore wind has been recently evaluated between £150 and £180/MWh in the UK (DECC, 2013c). In comparison, those of conventional generation are estimated around £75/MWh for standard gas generation (CCGT), £90/MWh for nuclear and between £100 and £150/MWh for coal generation[3]. Thus, the penetration of offshore wind is highly dependent on reducing the costs gap with conventional generation, which is reflected in the UK government support to the technology.

3. The UKENVI Model

The UKENVI model is a large scale, numerical, multi-sectoral, energy-economy-environment general equilibrium model for the UK. The model is a flexible framework that allows for a range of model closures, functional forms and key parameter values. The model has 25 industry sectors, detailed in Table 1, of which thirteen are energy sectors. Among energy sectors, we identify nine electricity generation sectors. Production inputs include primary factors, labour and capital, and intermediate purchases. The model includes three domestic institutional sectors: Firms, Households and Government. Previous versions of the UKENVI model have been used to evaluate the macroeconomic and sectoral effects of changes to energy efficiency and, in particular, the potential for rebound and backfire effects (Allan et al., 2007, and Lecca et al., 2014). The version of the model that we employ here has forward-looking agents and a fairly detailed set of energy sectors compared to previous configurations of the model and these new elements will be outlined here. The complete mathematical representation is provided in Appendix A.

For all sectors, the production functions used are Constant Elasticity of Substitution (CES) which allows for input substitution, when relative prices change (although Leontief or Cobb-Douglas functional forms are also available). All elasticities of substitution are required to be set for the CES functions where substitution is possible based upon previous estimates, which are listed in the next section.

The production structures are the same for all sectors with the exception of the electricity supply sector. The general production structure is illustrated in Fig. 1. For all sectors, gross output is produced by combining the composite intermediate inputs with the composite value added. It is possible to substitute between these two composites. Value added is produced by combining labour and capital inputs, also allowing for substitution. Intermediate goods can either be produced domestically or imported. Intermediate goods are a composite made up of two sub-composites of energy or non-energy goods[4].

Table 1
Sectoral disaggregation.

25 sectors	Sector title	123 sectors
1	Coal mining and quarrying	4
2	Gas mining and quarrying	5, 86
3	Coke ovens, refined petroleum and nuclear fuel	35
4	Other traded e.g. food and drink	6–19, 21–31, 34, 36–38, 77–80
5	Pulp and paper	32–33
6	Glass and ceramics	49–50
7	Clay, cement, lime and plaster	51–52
8	Iron and steel; non-ferrous metals	53–56
9	Generation - coal	85
10	Generation - gas + oil	85
11	Electricity distribution and supply	85
12	Generation - nuclear	85
13	Generation - hydro	85
14	Generation - biomass	85
15	Generation - wind	85
16	Generation - wind offshore	85
17	Generation - other	85
18	Generation - marine/solar	85
19	Agriculture; forestry and fishing	1–3
20	Water	87
21	Construction	88
22	Other manufacturing and wholesale retail trade	20, 39–48, 57–76, 81–84, 89–92
23	Air transport	96
24	Other transport	93–95, 97–99
25	Services	100–123

The energy composite can further be split into electricity supply and non-electricity. On the next level, non-electricity is a combination of coal and non-coal; where non-coal is a composite of oil and gas.

In this version of the model, the treatment of electricity inputs is distinctive. All sectors other than electricity supply purchase only a single electricity input from the electricity supply sector. However, the electricity supply sector has a different production structure from the others as shown in Fig. 2. In this case, the composition of energy inputs is more complex. While most of the production structure follows other sectors, the energy composite is structured differently. Electricity inputs are split between generation and supply activities. Generation is a composite of nine electricity-generating technologies[5], which act as competing inputs. These generation technologies are arranged into groups. First, generation is split between intermittent and non-intermittent technologies. Intermittent generators are renewable electricity technologies, which experience variability in their generation output depending on the resource, namely marine[6] and wind, with the latter being split between onshore and offshore. Among non-intermittent electricity generation technologies, we distinguish between fossil-fuel generators and low-carbon technologies. The fossil fuel generation combines both coal and gas generation. The low-carbon generation is a composite of nuclear and other renewables, distinguishing between hydro, biomass and landfill gas, which are combined on the next level of the CES production function.

By using these different production structures, we require that all sectors purchase their electricity inputs only through the electricity supply sector, which acts as an intermediate sector between electricity generation sectors and the rest of the economy.

In the forward-looking variant, the infinitely lived consumer chooses a sequence of consumption that maximizes the present value of utility,

[2] It is beyond the scope of the paper to investigate the causes of high cost of offshore wind power. The technology is still young and underdeveloped. Compared to onshore wind, installation, and maintenances costs are naturally more expensive and currently the levelised cost of onshore wind is around 50% lower than offshore wind. These become higher the larger the distance from shore. An interactive map of developments can be found on the Crown Estate website: http://www.thecrownestate.co.uk/energy-minerals-and-infrastructure/offshore-wind-energy/offshore-wind-electricity-map/

[3] The levelised costs of coal generation are higher than gas and nuclear, because of the binding requirement that new coal powered station must be equipped with carbon capture and storage technology.

[4] Introducing energy into the model is not straightforward. In particular, it is not clear where energy should enter in the production structure within the typical KLEM (capital-labour-energy-materials) nested production function. Energy could possibly substitute with or complement capital and therefore it could enter as part of a value-added composite. Alternatively it may enter the production structure as an intermediate input. Whatever assumption is made will affect substitution possibilities and simulation outcomes (see Lecca et al., 2011).

[5] We are not explicitly accounting for distributed generation explicitly. However, we are aware that this is a growing source of electricity and is expected to play an increasingly important role in helping especially to achieve UK's energy efficiency target.

[6] The Marine sector includes also electricity generation from solar. Solar power is a very tiny sector compared to the other energy sources, therefore, we encountered significant obstacles and complications to properly disaggregate and make this sector explicit in our production function.

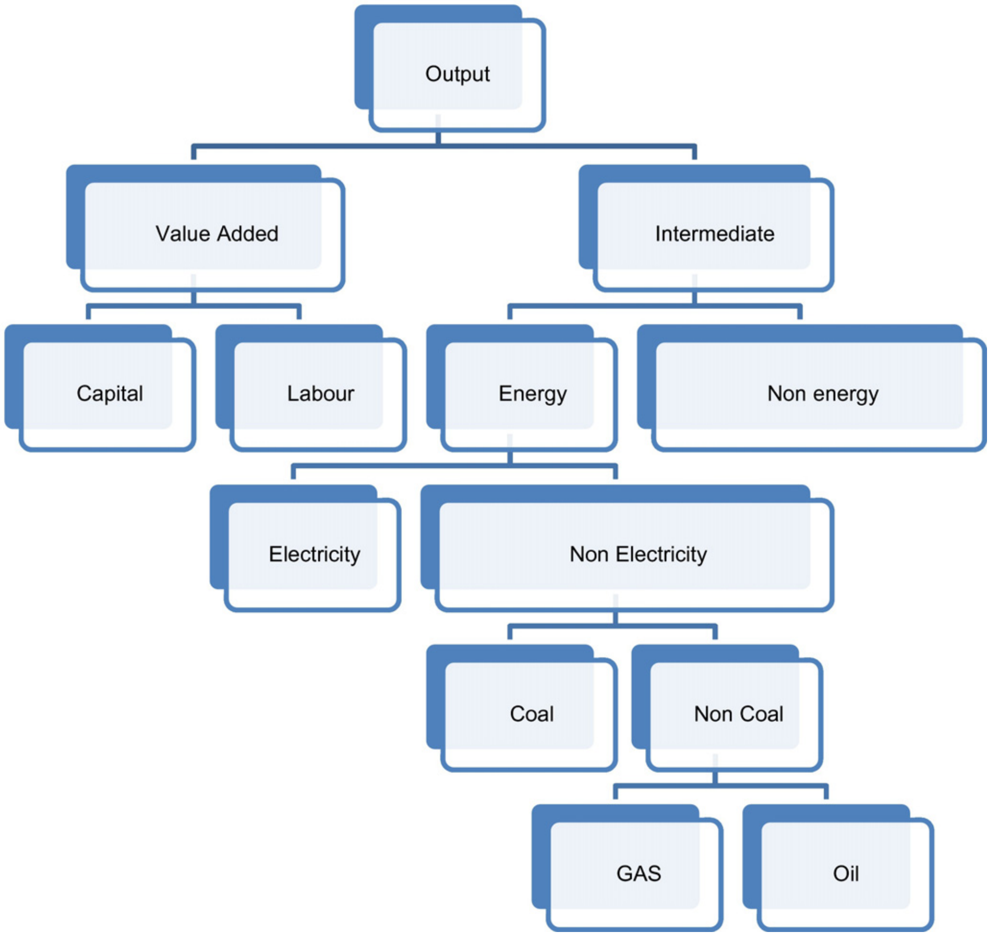

Fig. 1. General Production structure (except the electricity supply sector).

as summarized by the lifetime utility function which takes the following form:

$$\sum_{t=0}^{\infty}(1+\rho)^{-t}\frac{C_t^{1-\sigma}-1}{1-\sigma} \tag{1}$$

where C_t is the consumption at time period t, σ and ρ are respectively the constant elasticity of marginal utility and the constant rate of time preference. The dynamic budget constraint ensures that the discounted present value of consumption must not exceed total household wealth. Once the optimal path of consumption is obtained from the solution of the intertemporal problem, aggregate consumption is allocated intra-temporally between commodities through a CES function. Household demand for regional and imported goods is the result of the intra-temporal cost minimization problem and, similarly to the production side, domestic and imported commodities are imperfect substitutes.

In the forward looking model, investment is determined through profit maximising behaviour and is consistent with the assumption of quadratic adjustment costs. The base year assumes that capital stocks in each sector are initially in long-run equilibrium. When the model is solved period-by-period, net investments in each period adjust capital stocks.

We model the investment decision as in Hayashi (1982) where the rate of investment is a function of marginal q (or average q)[7] which is the ratio of the value of firms (VF) to the replacement cost of capital. Thus, the path of investment is obtained by maximizing the present value of the firm's cash flow given by profit,π_t, less private investment expenditure, I_t subject to the presence of adjustment cost $\theta(x_t)$ where $x_t = I_t/K_t$:

$$\begin{aligned}&\text{Max}\sum_{t=0}^{\infty}\frac{1}{(1+r)^t}[\pi_t - I_t(1+\theta(x_t))]\\&\quad\text{subject to } \dot{K}_t = I_t - \delta K_t\end{aligned} \tag{2}$$

The solution of the dynamic problem gives us the law of motion of the shadow price of capital, λ_t and the time path of investment related to the tax-adjusted Tobin's q (Tobin, 1969).

Wages are endogenous and population is fixed. The wage rate is determined through a wage bargaining function or wage curve (Blanchflower and Oswald, 1994) according to which real wages and unemployment are negatively related.

4. Dataset and Parameterization

The initial database used to calibrate the model is a Social Accounting Matrix (SAM) for the UK in 2010. This is based upon the UK symmetric Input-Output (IO) Table derived from the UK Supply and Use Table (ONS, 2014) together with data from income account (ONS, 2014). The UK income account is used to create the income-expenditure accounts for households, government, corporations, capital and external sectors and therefore complete the SAM, which is central to the construction of the baseline database.

The elasticities of substitution and other behavioural parameters are based on econometric estimation or best guesses. The empirical evidence related to the elasticity of substitution between domestic and

[7] As we are assuming that the firm is price taker, marginal q is equal to average q. For further details see Hayashi (1982).

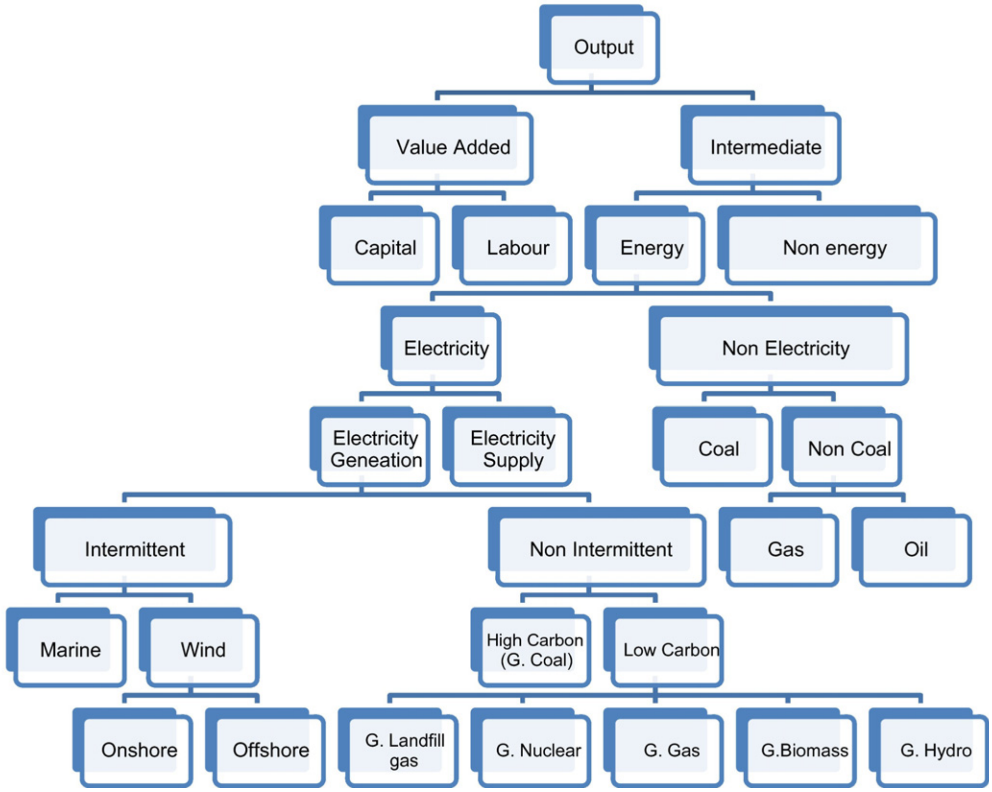

Fig. 2. Production structure for the electricity supply sector.

imported goods and services vary widely in the literature. For example, estimates of the Bank of England (Harrison et al., 2005) suggest Armington elasticity greater than 5, while Saito (2004), for a set of aggregate economic sectors found elasticities in the range of 0.8–3.5. Significantly lower elasticities are found in Hooper et al. (2000). Typically we would expect higher elasticity of substitution the higher the level of disaggregation (e.g.: sectors, countries) while lower elasticities are more likely to be found in cross-sectional analysis than time series analysis. Therefore, in the default case and for all sectors, we adopt a conservative approach by setting the Armington elasticity equal to 2. The price elasticity for export is set equal to 2 in line with Harrison et al. (2005) and Saito (2004)while the elasticity between labour and capital is equal to 0.3. This is consistent with empirical evidence shown in Barnes et al. (2008), Harrison et al. (2005) and Harris (1989).

Between energy and non-energy, electricity and non-electricity and between oil and non-oil, the value of the elasticities is based on the meta-analysis developed in Stern (2012). The estimates for the UK are in the range of 1.2–4.18. We take in this case a value of 2[8].

As for the elasticity of substitution between transmission and generation we think, it is plausible to assume a low response to price changes. Therefore, we set this equal to 0.3.

To date, evidence of the substitution parameter between renewable energy and specifically between intermittent and non-intermittent and clean and dirty electricity generations is scarce. As we will show in the next sections these parameters play a fundamental role in determining the outcomes of the model[9]. Empirical estimates found in Papageorgiou et al. (2016) suggest an elasticity of substitution between low and high carbon energy inputs in the range between 2 and 3. However, since we expect strong substitution possibilities, as innovation and more competition may increase the range of technologies, for all renewable electricity the elasticity of substitution is set to 5.

The interest rate faced by producers, consumers and investors is set to 0.04, the rate of depreciation to 0.15 and the constant elasticity of marginal utility equals to 1.2 (Evans, 2005).

5. Simulations and Results

DECC (2013c) proposes low, medium and high scenarios for the evolution of offshore wind costs from 2014 to 2030. According to these scenarios, summarised in Table 2, the levelised cost for the offshore wind energy in the UK is expected to fall by 2030 to £135/MWh, £115/MWh and £100/MWh in the high scenario, central and low scenario respectively[10]. Overall, these scenarios all assume broadly a 30% reduction in levelised costs of offshore wind by 2030 from 2014 levels. DECC has estimated that such a cost reduction should lead to modelling projections of around 22GW offshore wind deployment in 2030. The actual level of installed capacity is 3.7 GW, which corresponds to an increase in capacity of more than 600%.

The levelised cost reduction is translated into the UKENVI model as a permanent 30% increase in productivity in the offshore wind sector. Given that we do not have information about the evolution of the learning effects over time, we have raised the productivity of offshore wind sectors by 30% from the beginning of the shock. The alternative would have been to take the average over 20 years. However, since our focus is mainly on the long-run effects, the dynamics of the shock are of lesser importance. The increase in productivity applies to all factor inputs: capital, labour and intermediate inputs.

[8] In the meta-analysis developed by Stern (2012) the value of the elasticities of substitution for the UK are the following: 2.88 between coal and oil, 2.08 between coal and gas, 1.24 between coal and electricity, 2.39 between oil and gas, 1.91 between oil and electricity and 4.18 between gas and electricity. Given the lower weight of gas in our dataset and the production structure adopted in the paper (separating energy and non-energy, electricity and non-electricity and oil and non-oil) the value of 2 in each node of the nest seems a reasonable estimate.

[9] See also Acemoglu et al. (2012) on the importance of substitution elasticities between clean and dirty technologies.

[10] The model developed by DECC calculates the levelised cost as the ratio of the discounted total costs of a generic plant (including both capital and operating costs), to the discounted amount of electricity expected to be generated over the plant's lifetime.

Table 2
Projected levelised costs of offshore wind.

£/MWh	2014	2030
High	189	135
Central	163	115
Low	144	100

Source: DECC (2013c) Electricity Generation Costs (levelised costs with technology specific hurdle rates, p.25).

The model's equations are solved simultaneously for a given finite time horizon. We run the model for 30 years and the shock is maintained throughout. The population is fixed in the model; therefore the labour market adjusts through changes in the wage and unemployment rates in each period. In the first period of the model, sectoral capital stocks are constrained to their base year value to reflect short-run factor supply constraints. However, in the long run (which is imposed in period 2040) we relax the supply constraint allowing for full capital adjustment. In this time period, capital stock is at its optimum level where rental rates and user cost of capital are equalised. This also means that the accumulation rate is in its steady state equilibrium and therefore the change in the shadow price of capital equates to the replacement cost of capital.

5.1. Macroeconomic Impact

In Table 3, we report short-run and long run results for key economic variables expressed in percentage changes from the initial steady state equilibrium. The short run corresponds to the first period of the model over which capital stocks are fixed at base year values. The long-run solution of the model is reached in the last period of the model (period 50 in this case) where capital stocks have fully adjusted to the change in productivity. Population (identified in the model as working age population) is fixed. However, there is labour mobility among sectors, and total employment can vary with changes in the real consumption wage.

We observe that the productivity shock in the offshore wind sector is able to generate a substantial impact on the economy as whole, despite the size of this sector relative to the rest of the economy. (Recall that this sector accounts for only 0.026% of UK GDP in our base year.)

GDP increases by 0.03% and 0.15% from base year values in the short and long-run respectively. We also observe an increase in total employment and capital stock of 0.13% in the long run. These are lower than the increase in total value added, reflecting the increase in total factor productivity.

Population is fixed over time and the real wage is inversely related to the unemployment rate. Therefore the increase in labour demand reflected in the aggregate increase in employment reduces the unemployment rate in the short- and long- runs and consequently the real wage increases over both time periods, by 0.03% and 0.14% respectively.

In the short-run with capital stocks fixed, both the CPI and the replacement cost of capital increase, by 0.01% and 0.1% respectively. The stimulus to the prices of commodities creates adverse competitiveness effects. However, with full capital adjustment, both the CPI and the replacement cost of capital fall in the long-run. The downward pressure on prices provides a positive stimulus to competitiveness, so that the foreign demand for domestic goods and services increase. This is reflected in an increase in total exports of 0.07% over the long run.

In Fig. 3, we report the sectoral change in output with respect to base year values in both the short- and long-runs. While the initial small scale of the offshore wind sector limits the impact on aggregate variables, the sectoral distribution of output does exhibit significant changes, particularly in respect of the electricity generation mix. The productivity gains in offshore wind stimulate this sector's output, which increases by more than 200% in the long-run. However, substitution possibilities between the electricity supply sector's inputs lead to a drop in competing electricity generation sectors. All the electricity

Table 3
The impact of offshore wind development in UK. Results for key variables. Percentage change from base year values.

	Short-run	Long-run
GDP	0.03	0.15
CPI	0.01	−0.05
Unemployment rate	−0.25	−1.20
Total employment	0.03	0.13
Nominal wage	0.04	0.09
Real wage	0.03	0.14
Replacement cost of capital	0.10	−0.07
Households consumption	0.12	0.16
Investment	0.22	0.13
Electricity use-domestic	1.83	3.41
Electricity use-total	1.77	3.16
Capital stock	0.00	0.13
Export	−0.01	0.07

generation sectors from renewable energy source, except offshore wind itself, experience a significant reduction in output. This is around 6.5% from base year value in the long-run. Electricity generation from coal and gas also records a drop in output of a similar magnitude. Fuel extraction sectors (i.e., coal and gas) also suffer from this crowding-out of output, as they provide a large proportion of inputs to fossil-fuel electricity generation sectors. The electricity supply sector is stimulated overall; as reported in Table 3 the industrial use of electricity increases by 3.41% and its total use rises by 3.16% relative to base year values. Furthermore, although the magnitude of the stimulus is small the increase in offshore wind productivity generally positively impacts non-energy sectors (manufacturing and services). Overall, non-energy output increase around 0.14% from base year values.

5.2. CO2 Emissions and Elasticities of Substitution

Although we observe an overall expansion in the economy, the substitution away from fossil-fuel sectors towards a low-carbon generation technology, offshore wind in this particular case, has the effect of curbing total CO2 emissions which fall by 25 Mt CO2e in the long-run. However, the impact on CO2 emissions proves to be sensitive to the values of the elasticities of substitution in the nested production structure, and in particular amongst generation technologies.

In the simulation results presented so far, we have hypothesized relatively high elasticities in the energy supply sector. If we were to reduce these elasticities, we would expect lower substitution towards the more productive offshore wind generation sector away from fossil-fuels, and consequently a lower reduction in CO2 emissions. In contrast, an increase in these elasticities is likely to generate instead a greater reduction in CO2 emissions. Fig. 4 plots the evolution of the changes in CO2 emissions in million tonnes (Mt) to 2040 for three different set of elasticities reported in Table 4. In this table, the first column gives the default values used in the analysis so far. In the second column, we decrease the elasticity of all renewable electricity sectors and the elasticity of substitution between low and high-carbon energy technologies, while in the third column, these are augmented.

As expected, Fig. 4 shows that increasing the elasticities of substitution has a greater impact in reducing CO2 emissions. The opposite occurs when these elasticities are reduced, and CO2 emissions actually increase in this case, given that the output of conventional energy sources are also rising. With higher elasticities, the long run CO2 reduction is about 50 Mt e compare to 20 Mt e when we use default elasticities.

5.3. Offshore Wind Capacity Projections

In Fig. 5, we plot, for a range of possible levelised costs of offshore wind energy, the associated increase in offshore wind capacity. On the vertical axis, we show the levelised cost in £ per MWh and on the

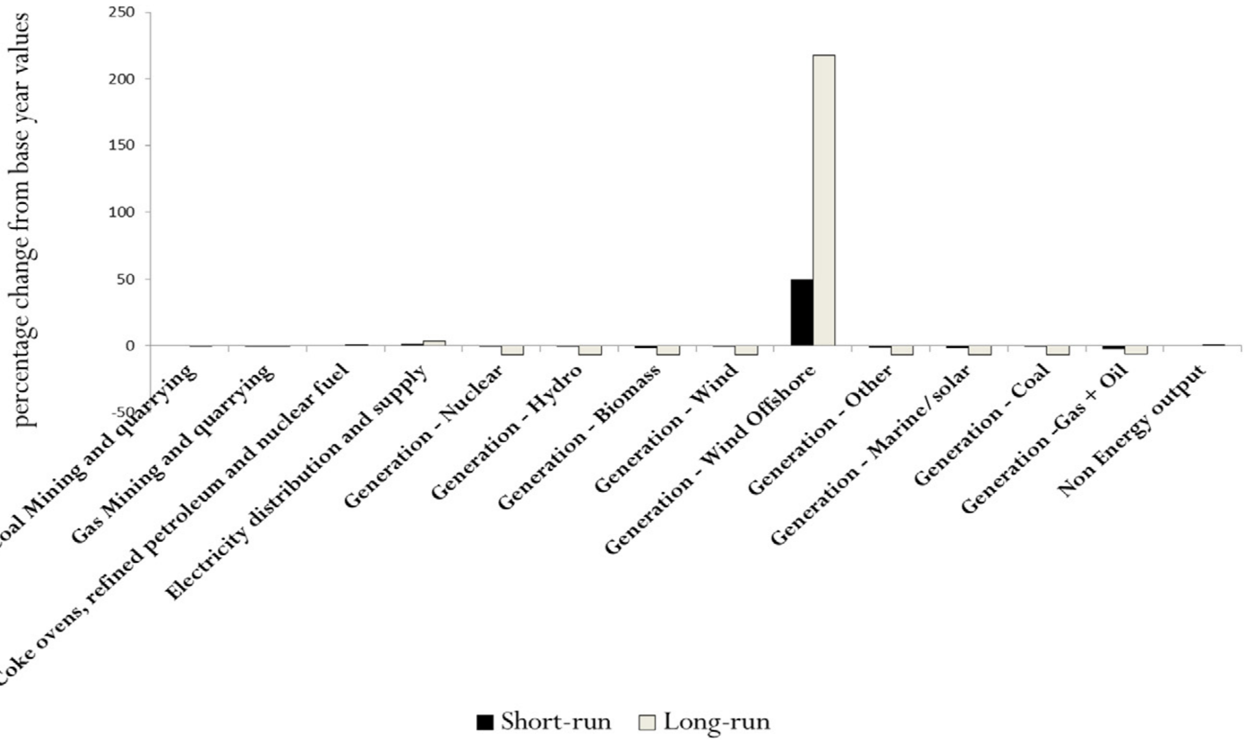

Fig. 3. Sectoral impact.

horizontal axis the potential expansions in offshore wind capacity expressed in GW. The relationship between the levelised costs and offshore wind capacities generated by our modelling experiment is shown for the three different sets of elasticities of substitutions reported in Table 4. Also, for the high elasticities we report results for two different agents' behavioural model closures: myopic and forward-looking agents. In the former case firms and consumers are myopic: investment is driven simply by rental rates relative to user costs and by the

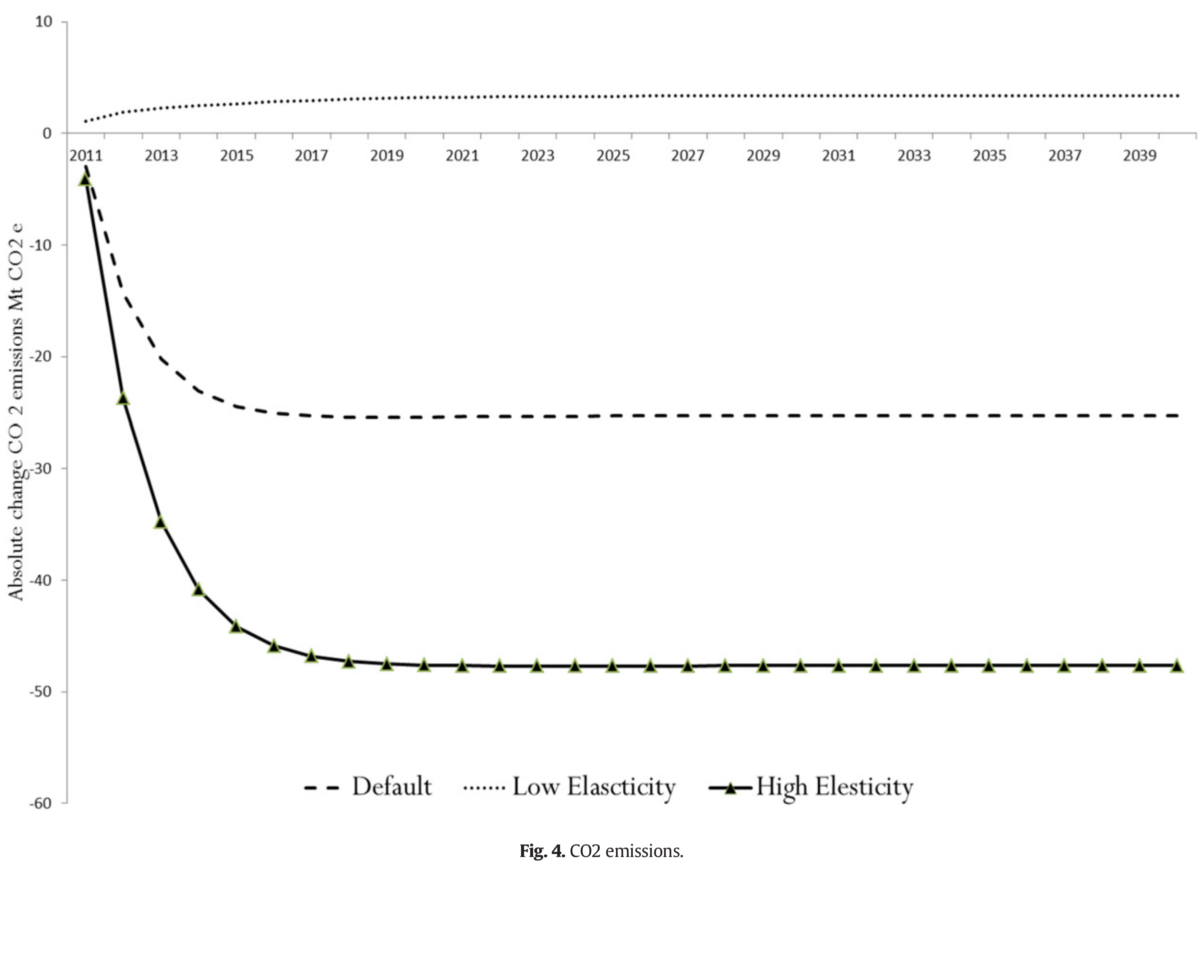

Fig. 4. CO2 emissions.

Table 4
Elasticities of substitutions - 3 scenarios.

Elasticities	Default	Low	High
Intermediate-value added	0.3	0.3	0.3
Energy and non-energy	2	2	2
Electricity and non-electricity	2	2	2
Oil and non-oil	2	2	2
Low and high carbon	5	2	8
Transmission and generation	0.3	0.3	0.3
Intermittent and non-intermittent	5	2	8
Between non-intermittent	5	2	8
Wind and marine	5	2	8
On and off shore wind	5	2	8
Between non-energy	0.3	0.3	0.3

(quadratic) costs of adjusting actual to desired capital stocks, and consumption is constrained by current income. When firms and consumers are forward looking, investment and consumption adjust more rapidly because transactors correctly anticipate the longer-term outcomes.

According to DECC's (2013b) central scenario, reduction in the levelised costs of offshore wind to around £100/MWh could lead to 22 GW capacity by 2030. Our modelling exercise has however shown that this target could be very difficult to reach, if not accompanied by other policy measures. In the default case, FL default in Fig. 5, (using default elasticities of substitution), a levelised cost of £100/MWh, modelled as a 30% increase in productivity in the offshore wind electricity generation sector, generates an increase to 11.5 GW capacity by 2030. This is significantly below

DECC's projections.

With lower elasticities of substitution, the curve representing the relationship between the levelised cost and capacity becomes steeper, rendering it more difficult to achieve the target, even with a significant reduction in offshore wind levelised costs. The higher the elasticities of substitution among electricity technologies, the closer the model can approach the 22 GW capacity projections in offshore wind. Indeed with forward-looking agents, the capacity target is likely to be hit by 2030 only with high elasticities in the renewable sectors. If agents are myopic, a levelised cost slightly below £90MWh by 2030 would be required to secure the capacity projected by the government.

6. Conclusions

In this paper, we focus on the economic and environmental impact of technology-driven reductions in the cost of offshore wind. In particular, we explore the impacts of the “learning rate” implied by the most recent cost projections developed by the UK Department of Energy and Climate Change (DECC).

DECC's (2013c) longer-term projections of offshore wind deployments, proposes low, medium and high scenarios for the evolution of offshore wind costs. All of these scenarios assume a 30% reduction in levelised costs of offshore wind by 2030 from 2014 levels. DECC (2013b) estimates that this reduction in total costs of offshore wind electricity generation is sufficient to achieve 22 GW of offshore wind capacity by 2030. That is to say, sufficient to ensure a greater than 600% increase in capacity from current levels.

Our model suggests that this target could be difficult to achieve, especially if substitution among generation technologies is limited and agents are myopic. It is, however, important to note that our modelling approach in this paper focuses only on costs reductions in offshore wind, whereas the capacity scenarios presented in DECC (2013b) are based on a number of complementary assumptions and projections, relating to the electricity supply system as a whole. We have abstracted

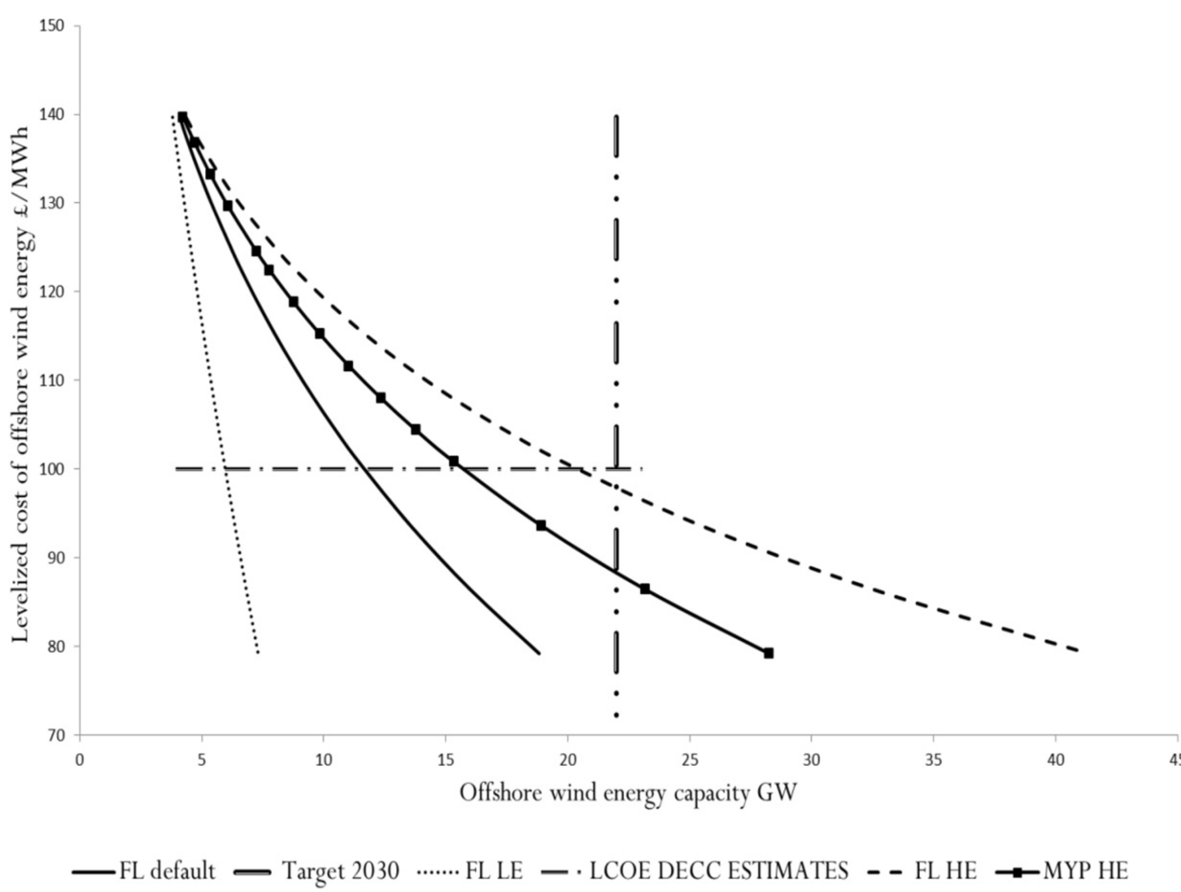

Fig. 5. Relationship between the levelised costs and offshore wind capacities generated by UKENVI model.

from these, to focus solely on the system-wide impacts of the "learning rate" assumptions in DECC's analysis. For example, DECC's projections seek to account for other policy support for generation technologies (e.g., contracts-for-differences), regulatory constraints (e.g., fossil-fuel plant closures, carbon price), technical constraints (e.g., capacity building limits) and external constraints (e.g. fossil-fuel price projections). These constraints are likely to further encourage the development of renewable technologies, including offshore wind, in accordance with the decarbonisation policy objective of the government.

On the other hand, the electricity-supply model used to generate DECC's projections does not take into consideration the wider energy-economy-environment interactions, and the integration of the electricity sector within the wider UK economy, but uses external (exogenous) electricity demand projections. Our simulations reveal that technological change in offshore wind imparts a beneficial supply-side stimulus to the UK economy that increases both exports and investment, in line with the UK Government's stated desire for "rebalancing". Furthermore, in the present context this is achieved with a simultaneous increase in consumption, rise in real wages, and reduced inflationary pressure. This represents an important positive contribution to the UK macroeconomy that would not be identified by conventional energy systems models.

Another significant and distinctive result of this paper is that, despite the economic expansion generated by the technological improvements in the offshore wind electricity generation sector, total CO2 emissions actually decrease, as the electricity-mix becomes less fossil-fuel intensive. While this result does depend to a degree on the ease with which electricity generated by offshore wind can substitute for conventional generation technologies, it demonstrates the real potential to secure a "double dividend" for policy: in that both economic and environmental objectives are likely to be positively impacted[11].

The UK government did not allocate the new round of contracts due initially to be released in October 2015, but postponed this until further notice. This is unfortunate, since our analysis suggests that the expected reduction in costs through a learning curve predicted by DECC would be insufficient to generate the necessary private sector investment in offshore wind projects. Subsidies through the contract for differences scheme are crucially important to support investment in new low carbon generation. Furthermore, expectations of future policy are important in influencing the speed with capacity is likely to expand. Continuing delay and lack of clarity over the timing and budgets for the next CfD allocation may compromise the UK targets on low-carbon electricity generation.

Our analysis is subject to a number of limitations. First, while the model captures the sensitivity of the system to induced price, income and output changes, the specification of the electricity system lacks the level of detail often incorporated in energy systems models. Second, the scarce evidence relating to the elasticity of substitution parameters between energy and non-energy inputs on the one hand and between clean and dirty technologies, increases the degree of uncertainty around the results.

In this paper we focus primarily on the system-wide or macroeconomic implications of a given pre-defined learning effect in the offshore wind sector. The results of our study emphasise the potentially beneficial effects both for the UK macroeconomy and for emissions. Our study complements those derived from energy system optimization models which include a detailed description of the technical components of the energy system. Both types of models enhance our understanding of the impacts of policy and other disturbances, and there is real potential for exploring the development of hybrid models that capture the strengths of both CGEs and energy systems models.

[11] In fact, it could also be argued that security of supply is enhanced as a consequence of reduced energy imports, creating a triple dividend.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2017.01.021.

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