Concurrent and legacy impacts from establishing a marine energy sector in Scotland: a computable general equilibrium analysis

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Abstract

In Scotland, significant reductions in electricity generation capacity are expected as coal- and nuclear power stations close. Although the UK Parliament makes decisions on energy supply, the Scottish executive has responsibility for encouraging renewable technology development and has set ambitious targets for renewable generation. Allowing for constraints imposed by resource availability, economic viability and technological feasibility wave power alone could generate capacity in excess of 3GW.

In this paper, we examine the economic impact that the installation of 3GW wave energy capacity would have on Scotland. We estimate the costs that may be incurred to construct and install this level of capacity between now and 2020 and the subsequent expenditures required to operate and refit the generators during their 20-year life. A regional computable general equilibrium (CGE) of Scotland, AMOSENVI, is then used to estimate the scale of the economic impact, in terms of GDP and employment, of these expenditures. The scale of these economic impacts over the lifetime of the devices is significant, and there are also substantial “legacy” effects that persist beyond the design life of the devices. These results illustrate both the importance of looking beyond the duration of direct expenditures when considering the scale of economic impacts, and also the potential economic benefits to Scotland from the development of an indigenous marine energy industry.

1. Introduction and policy background

The recent UK Energy Review (DTI, 2006, p.15) concluded that:

Over the next two decades, it is likely that we will need around 25GW of new electricity generation capacity, as power stations – principally, coal and nuclear plants – reach the end of their lives and close. This will require substantial new investment and is equivalent to around one third of today’s generation capacity.

For both environmental and energy security reasons, there is a growing recognition that existing fossil fuel technology cannot continue to be as heavily used as in the past and there is a growing movement towards generation technologies which operate with low, or zero, carbon emissions. This includes renewable technologies, such as hydro, on- and off-shore wind, and marine (wave and tidal) devices. The use of wind technology to generate electricity has grown rapidly across the UK in the last decade. However, other renewable technologies, such as marine, have also received both financial support and political interest and the first generation of economically viable devices is now close to market¹.

Like the UK, a similar situation applies in Scotland (Allan et al, 2006a; Royal Society of Edinburgh, 2006). Within twenty-five years all the existing major electricity generation facilities in Scotland could be closed (RSE, 2006).

While energy supply decisions are strictly a matter reserved for the UK Parliament, the Scottish Executive has ambitious targets for renewable generation. These targets are to provide 18% of the electricity generated in Scotland by 2010 and 40% by 2020 from renewable sources (Scottish Executive, 2003). Expressed in absolute terms, the Scottish Executive (2005) has accepted the Forum for Renewable Energy Development in Scotland (FREDS, 2005) target of

1 Ocean Power Delivery (OPD)’s device – the Pelamis – has received an order from a Portuguese consortium to build the world’s first commercial facility to generate electricity from ocean waves, which is due begin production in late 2006. As the Managing Director of OPD, Richard Yemm said, “The Portuguese government has put in place a feeder market that pays a premium price for electricity generated from waves compared to more mature technologies such as wind power.” (OPD, 2006)
6GW of installed renewables capacity, a substantial growth given present capacity of 2.8GW\(^2\).

The extra capacity required to meet the Scottish Executive targets is intended to come from a range of sources. There are no specific targets for the amount of electricity to be generated by each renewable technology. However the Scottish Executive has launched a consultation on the ways in which the Renewable Obligations (Scotland) could be amended to support generation of electricity from wave and tidal resources (Scottish Executive, 2006). Boehme et al (2006) argue that, after applying constraints concerning resource availability, economic viability and technological feasibility, wave power could contribute an installed renewables capacity in excess of 3GW.

In this paper, we examine the economic impacts that the installation and operation and maintenance of such a capacity of wave energy would have on Scotland. Essentially we treat the generated electricity either as being exported to the rest of the UK or acting as a substitute for imported electricity. We assume this capacity is provided by the installation of a number of wave energy devices of the articulated attenuator type. The investment characteristics are outlined in Section 2, together with the details of the central case simulation used in the remainder of this paper. In Section 3 we outline the AMOSENVI Computable General Equilibrium (CGE) model of Scotland and in Section 4 we report “central case” results. In Section 5 we report key findings from extensive sensitivity analysis. Section 6 offers conclusions and outlines the implications of these results for energy policy in Scotland and the UK.

2. The time profile of construction, installation and operating expenditures

The illustrative wave energy device chosen in this exercise is of an articulated attenuator type (as described by Boehme et al, 2006), consisting of four thirty-metre cylindrical steel sections joined together by three independent hydraulic power conversion modules. Each device has a total steel weight of 380 tons, a rated power output of 750kW and an average power output of 263kW. As shown by Boehme et al (2006) the average power capture from a device varies with device location but the mean capacity factor of 35% used here may be observed for 3GW of wave power installed in Scottish waters. When deployed as part of a wave farm, multiple devices are installed in an array formation. In this section, we calculate the time profile of expenditures required to install 3GW wave energy capacity in Scotland by 2020 and the subsequent operating and refit expenditures over that capacity’s lifetime. To attain a cumulative installed wave capacity of 3GW, four thousand devices must be installed by 2020. We assume that, in reaching 3GW of capacity by 2020, the installation of wave energy devices follows an exponential growth path similar to that displayed by the wind energy sector over the last decade.

The assumed absolute and cumulative total number of devices installed at the end of each year is shown in Figure 1. Initially around 30 devices are installed per year but this increases to seven hundred devices installed during the year 2020. Each of the wave devices installed has a lifetime of 20 years, with a refit scheduled to occur after the device has been installed for ten years.

2.1 Installation expenditures

Figure 1 gives the time-exponential growth of annual physical investments needed to hit the 2020 target for the cumulative installed capacity. Subsequently, we calculate the total investment made each year as the product of the electrical output generated by the devices installed during that year (kWh) and the present value of each generated unit of electricity (£/kWh). Whilst it is recognised that power capture is dependent on numerous parameters, we employ a simple estimate of total electrical output for N devices operating for 20 years: \(N \times \text{average output (262kW) } \times 20\text{ years.}\)

Following the carbon trust (2006) the cost of electricity is taken as 8.5p/kWh under the assumptions that renewable subsidies valuing 3.5p/kWh persist till 2020 and that the cost to generate electricity from fossil fuel based generators will increase to around 5p/kWh. Having estimated a total investment per annum, we use published information (Previsic et al, 2004) for this type of wave energy device to calculate the total installation costs and the subdivision of these costs between different expenditure categories. Each of these expenditure categories is then allocated to an appropriate Standard Industrial Classification and AMOSENVI\(^3\) sector as described in Table 1 below. Note that the direct impact of installation is concentrated in two sectors, 10 and 11, which receive 35% and 57% respectively of this expenditure.

Not all of these installation expenditures will be made in Scotland, or on products produced in Scotland. The extent to which each component can be sourced from within Scotland significantly affects the economic impact felt by the region.

Information on the imported content of these expenditures is uncertain, particularly given that we are considering future expenditures.\(^2\) It is likely that certain elements of the installation expenditures with high transport costs will be made close to where the devices are installed (such as the concrete structures or steel inputs). The decision as to the source of materials and components will be made by the device developer, presumably on the basis of the lowest cost source that satisfies the design requirements for each input. In the “central case” simulations we make assumptions about the degree to which each component of capital

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\(^1\) A detailed breakdown of the sectors in the AMOSENVI model is presented in Appendix 1 of Allan et al (2006c).

\(^2\) As of the end of April 2005.

\(^3\) For example, with wind generated electricity the import content is extremely high, while for other generation technologies, there is a much more local input-sourcing (Allan et al, 2006a).
expenditure is made within Scotland. These are given in column six of Table 1. We assume these proportions are fixed across all time periods of the simulation, so that, for example, the same percentage of total spend on underwater cables is made in Scotland in 2006 as in 2020.

In the central case scenario, concrete structures, construction facilities, installation and construction management are all assumed to have high Scottish content. The main element in terms of value is the power conversion module. It is likely that companies able to provide components for these will be located outwith Scotland unless significant development in large-scale production of these specialised modules develops to serve the marine energy sector directly. Thus, we assume that only half of the total values of these expenditures are made directly in Scotland. As a result of these import elements, the local direct impact of the installation expenditure is reduced but the AMOSENVI sectors 10 and 11 still dominate.

2.2 Operating expenditures

Operating expenditures are small when compared to the initial costs for each device. However, these expenditures continue for the operating life of the device (here taken as 20 years). Operating expenditures however, are difficult to predict as they include planned and unplanned maintenance, and monitoring costs.

Maintenance costs will depend upon several factors, including the accessibility of the site by vessel, the duration for which wave conditions are suitable for site access, and the reliability of the installed devices which will be affected by the severity of extreme conditions at the design site. We again assume that a certain portion of the value of the operating expenditures is made in Scotland. For the three main elements of the operating expenditures, we assume the following: labour 95%, parts 75%, insurance 95%. Since the majority of parts are likely to be components of the power conversion module, this expenditure is allocated to the industrial sector SIC 29.1. Insurance expenditures were allocated to the “Communications, finance and business” sector in AMOSENVI (Sector 17). Operating expenditures made up 51.9% of total expenditures over the design lifetime of the devices.

2.3 Refit expenditures

Ten years after installation, the devices must be removed from their site at sea for a complete overhaul and refit. This might include re-painting, but is likely to include the exchange of some of the power take off elements – such as the hydraulic rams (Previsic et al., 2004). Expenses at this time are in two categories; operation costs and parts. We assume that 90% of the operation expenditures are made in Scotland, and 50% of the parts for the refit are sourced in Scotland (since most of the replacement parts cost will be for the power conversion module). The refit operation costs were allocated to the Construction sector (SIC 45), while parts were again treated as coming from SIC 29.1. Total refit costs over the lifetime of the devices made up only 4.2% of all expenditures.

The time variation of the three Scottish expenditure elements: installation, operation and refit, are shown in Figure 2. Each expenditure stream includes all the judgements made above about the Scottish content of each expenditure component. In the absence of more detailed information, we assume that decommissioning costs incurred at the end of the devices expected lifespan are negligible.

3. Outline of model and simulation strategy

3.1 AMOSENVI model

The AMOSENVI model is explained in full in Hanley et al (2006). This is a variant of the AMOS Computable General Equilibrium (CGE) model of Scotland (Harrigan et al, 1991), developed specifically to allow the investigation of environmental impacts. It is calibrated on a social accounting matrix (SAM) for Scotland for 1999. AMOSENVI has 25 commodities and activities, five of which are energy commodities/supply. These sectors are listed in Appendix 1 of Allan et al (2006c).

The AMOSENVI framework allows a high degree of flexibility in the choice of key parameter values and model closures. However, a crucial characteristic of the model is that we impose cost minimisation in production with multi-level production functions, generally of a constant elasticity of substitution (CES) form, so that there is input substitution in response to relative-price changes. We impose a single Scottish labour market with perfect sectoral mobility. We also generally assume that wages are subject to an econometrically parameterised regional bargained real wage function (Layard et al, 1991).

All simulations described here are run in a multi-period setting, given our interest in the period-by-period impacts of a series of transitory expenditure shocks. These periods are interpreted as years, in that we have used annual data where we econometrically parameterise relationships. In each of these periods both the total capital stock and its sectoral composition is fixed, and commodity markets clear continuously. However, each sector’s capital stock is updated between periods via a simple capital stock adjustment procedure.

In a similar manner to the updating of capital stocks, the net migration flows in any period update the population stocks at the beginning of the next period. We assume a migration specification in which net migration into Scotland is positively (negatively) related to the real wage (unemployment rate) differential between Scotland and the rest of the UK. The regional economy

5 Allan et al (2006b) gives the UK national version of the model: UKENVI, and a fuller version of this section can be found in Allan et al (2006c)

6 AMOS is an acronym for a micro-macro model of Scotland.
is assumed to have zero net migration in the base year and net migration flows re-establish this equilibrium.

3.2 Simulation strategy

In each of the first thirty-five periods, the appropriate sectorally disaggregated installation, operation and refit expenditures are entered as exogenous shocks to final demand. The model is then run forward for a further 65 periods with no additional exogenous shocks. It is important to state that AMOSENVI is not a forecasting model. The economy is assumed to be initially in equilibrium so that if it runs forward with no exogenous shocks it simply replicates the base year values. Therefore, the simulation results reported here are in comparison to a constant base scenario and so all results, are due to the direct or indirect effect of the positive demand disturbance.

4. Central case scenario results

Figure 3 gives the aggregate direct expenditure shocks, presented in Figure 2, together with the GDP results generated by the AMOSENVI model. In the period when installation of the marine capacity is completed, 2020, the GDP increase is at its maximum value of £420.24 million. However, note that the expansion in GDP is much lower than the increase in expenditure. There are two reasons for this. First, although all expenditure is on Scottish commodities, intermediate inputs produced outwith Scotland fail to contribute to Scottish GDP. Second, GDP will fall in some sectors due to loss of competitiveness incurred by crowding out as the expansion in demand increases both wages and the price of intermediate inputs.

However, the steep drop in exogenous expenditure that occurs in 2021 is not accompanied by a correspondingly steep fall in GDP. GDP does decline, but by a relatively small amount, and it rises modestly in the second phase of activity up to 2029. After 2030, when refit expenditures cease and operational expenditures continue to decline, the GDP effects are actually greater than the direct expenditure impacts and these GDP effects continue after 2040 even when direct expenditures have ended. Essentially these initial expenditures lead to an increase in factor supplies (of capital and labour) that have a subsequent “legacy” impact, an impact that remains even after the installation expenditures cease.

Figure 4 gives the simulation impacts on total employment generated by the introduction of the marine technology. The variation in total employment is qualitatively similar to the variation in GDP. We observe the same spike at 2020, where the employment increase equals fifteen and a half thousand jobs, prior to a gradual increase over the period 2021-2029 and the subsequent slow decline.

The change in working age population is also plotted in the same diagram. Note that this is a change in population brought about solely through increased net migration only; we do not here model “natural” demographic changes. This positive net migration is a response to the tightening of the labour market. However, once the installation stage stops, the additional population (and work force) is a key factor in the subsequent legacy effects.

In Allan et al. (2006c) we show that there are clear sectoral differences within this aggregate result. There will be crowding out of activity, away from sectors not directly affected by the demand stimulus, while sectors experiencing the demand injections will experience increased output. Two key features of CGE models are their generally high level of sectoral disaggregation and the active supply-side. Conventional macro-models have very limited sectoral disaggregation, whilst demand driven modelling approaches, such as standard Input-Output (IO), cannot allow for crowding out effects.

In the “stimulated” sectors, i.e. those that receive a direct exogenous demand stimulus as a result of the expenditures, prices increase, stimulating both output and the return on capital and subsequent investment and therefore capital stock. The non-stimulated sectors are subject to both positive and negative impacts that result from the expansion of the stimulated sectors. For these sectors, the output effects are more muted and initially more varied (Allan et al 2006c). Up to 2020, the impact on the majority of these sectors is small but negative. Again, at 2020 there is a discontinuous adjustment for all sectors as the installation phase ends. However in the second phase of direct expenditures to 2030 the output of all non-directly stimulated sectors increases. By 2037 all non-directly stimulated sectors have an output greater than their base year value and this positive output relative to the base year continues for all these sectors, even when all the direct exogenous expenditures stop in 2040.

The real and nominal wage changes are charted for the central case scenario in Figure 5. In those periods where there are significant exogenous expenditures (essentially up to 2030), there is upward pressure on wages and the increase in the nominal wage means that some exports are crowded out in order to facilitate the increase in installation and refit activity. However, once the direct expenditures stop in 2040, the lower nominal wage acts as a stimulus to the Scottish economy and it is primarily this that produces the large legacy effects.

5. Sensitivity analysis

An advantage of using a CGE model is that it is straightforward to test how sensitive the simulation results are to assumptions. This is especially useful when performing ex ante scenario analysis as we are here. We have stressed in our central case scenario the

7 The working age population is taken here to be all those between the age of 16 and 64.
importance of the legacy impacts that flow from the effect that the initial demand shock has on increasing the supply of labour and capital through the migration and investment functions. We investigate sensitivity to these two functions and remove both the substitution possibilities and supply constraints from the model to configure it as a demand driven dynamic IO system. Full sensitivity results can be found in Allan et al (2006c), but key findings are outlined below.

5.1 Migration sensitivity

- GDP and employment are sensitive to large changes in specification of the migration function.
- Increasing wage and unemployment coefficients increases the sensitivity of migration to these economic factors and so: increases the maximum impact on population change; reduces the time until this maximum impact is attained; and increases the rate at which population effects subside.
- A larger “legacy” impact is observed when migration is made less responsive. This reflects the longer period over which population continues to increase, and the slower subsequent population decline, where the reaction of migration to changes in economic activity is more damped.

5.2 Varying investment sensitivity

- When the capital adjustment speed is increased, the GDP impacts in those periods where there are direct exogenous expenditures are greater. Also, the economy responds more rapidly to reduce the capacity constraints generated by the demand injection.
- When the adjustment speed is reduced, the legacy impacts are reduced in a similar manner to the migration results.

5.3 Dynamic Input-Output

Typically, in the UK at least, a dynamic IO system would be used to identify the aggregate impact of the type of exogenous expenditure injection modelled here. For comparison the CGE model is reformulated as a dynamic extended IO system by imposing fixed coefficients at all levels of the production function, removing any capacity constraints in the production of value added and imposing a fixed real wage closure in the labour market. This means that demand in any sector can be met at the existing price and so no supply constraints operate to limit the expansion of the directly and indirectly stimulated sectors. Similarly there are no cost changes to generate crowding out effects. This demand driven model predicts:

- An increase in GDP three times the value of that under the central case scenario by 2020.
- Strong reaction to the subsequent (post 2020) reductions in the exogenous expenditure associated with the introduction of the marine energy devices.

- Almost no activity change after the operating expenditures end in 2040.

5.4 Present value of main aggregate impacts

Figure 6 shows the cumulative GDP effects over the 100 year time period subdivided into three sub-periods: the installation phase 2006-2020, the refit and operation phase 2021-2040 and the period after 2040 when there are no further expenditure injections. GDP is shown both undiscounted and discounted according to discount rates suggested by the Green Book (HM Treasury, 2003) that are intended to reflect social time preference.

It is clear from the GDP totals that the introduction of a marine energy sector in the Scottish economy would generate a significant stimulus to GDP over a long period of time. However, different results are observed for the discounted totals, not only in terms of the absolute size but also the qualitative relationship between the different simulations. Discounting gives greater weight to the results in the earlier years so that simulations that deliver GDP earlier are favoured. This means that the present value of the GDP stream is maximised under the dynamic IO model.

If we compare the time sequence of effects across the different simulations, these observations are extended and reinforced. First, for all simulations, the undiscounted cumulative GDP impact over the twenty-year period 2021-2040 is greater than the impact over the fifteen-year period 2006-2020 when the installation expenditures occur. This is even the case with the undiscounted dynamic IO simulation. Second, only for the migration off and the dynamic IO simulations are the undiscounted legacy effects, that is those that occur after 2040, lower than the impacts in the initial, installation period. Third, when we discount, the value of the legacy effects are reduced but they remain important in most cases.

6. Conclusions and policy recommendations

Electricity generation in the UK will undergo considerable changes over the next twenty years. There will be increased generation from renewable sources, especially wind (both on- and off-shore), but also wave and tidal technologies, as incentive schemes make these technologies economically viable. The installation of 3GW of wave energy capacity around the coast of Scotland is technically possible (Boehme et al, 2006), but would require significant expenditures across a range of sectors. In this paper we have sought to quantify the macroeconomic impact that these expenditures could have on Scotland over the operating lifetime of 3GW capacity.

We find that these expenditures can potentially deliver a significant economic benefit to the region. For the central case scenario, the present value of discounted

\[\text{1 The small effects that there are come from residual capital and population adjustments impacting on investment demand and consumption demand through household income.}\]
GDP change is £5,466.2 million. This additional Scottish GDP is not only created over the lifetime of the investment, but continues for many years into the future, partly due to the positive net migration and additional investment into Scotland which accompanies the extra expenditures.

Whilst these GDP effects appear substantial, these results are based upon the assumption of an upper bound unit electricity value of 8.5p/kWh, which might not be realised. Further, the sub-division of investment between energy sectors is based on the installation of a specific type of wave energy device at a generic location. A different sectoral breakdown would be required to model the economic impact of other device concepts.

These results are important for policy makers. If Scotland is able to use the potential that marine power has for electricity generation, this will not only be beneficial environmentally but also will give a positive boost to Scottish GDP, employment and population. This boost will be increased by integration of the marine energy sector into the local economy: i.e. the greater the proportion of locally sourced installation, operation and refit expenditures, the greater the positive impact on Scotland. Failure to establish a technical knowledge base in Scotland could result in the elements produced in Scotland consisting of the low-value generic engineering components only whilst the high value elements are imported.

Also, it is apparent that in appraising the impact of a project in an open regional economy, one should consider not only the period over which the direct expenditures or activities related to that project are made, but also look beyond that horizon to the longer term. Essentially positive net migration and additional investments made directly or indirectly in response to the project produce supply-side effects that can be very long lasting.

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References


**Figure 1:** Cumulative total number of devices and annual number of devices installed, 2000 to 2020

**Figure 2:** Total annual expenditures in Scotland under central case scenario, £millions

**Figure 3:** Absolute differences in GDP from base and expenditures, £millions

**Figure 4:** Absolute differences in employment and change in working age population

**Figure 5:** Real and nominal wage values in central case, % change from base

**Figure 6:** Comparison of both GDP and discounted GDP impacts for central case and sensitivity simulations

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**Table 1: Installation expenditure categories, shares and industrial sectors**

<table>
<thead>
<tr>
<th>Expenditure category</th>
<th>Expenditure share</th>
<th>Industrial sector</th>
<th>SIC</th>
<th>AMOENVI sector</th>
<th>Scottish share</th>
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<tbody>
<tr>
<td>Onshore transmission and grid upgrade</td>
<td>1%</td>
<td>Electric motors and generators</td>
<td>31</td>
<td>11</td>
<td>75%</td>
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<tr>
<td>Undersea cables</td>
<td>5%</td>
<td>Electric motors and generators</td>
<td>31</td>
<td>11</td>
<td>75%</td>
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<td>Spread mooring</td>
<td>10%</td>
<td>Structural metal products</td>
<td>28.1</td>
<td>10</td>
<td>75%</td>
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<td>Power conversion module</td>
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<td>Concrete structures</td>
<td>20%</td>
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<td>95%</td>
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