Allan G, Bryden I, McGregor PG, Stallard T, Swales JK, Turner K & Wallace R (2008) Concurrent and legacy economic and environmental impacts from establishing a marine energy sector in Scotland, *Energy Policy*, 36 (7), pp. 2734-2753.

This is the peer reviewed version of this article

Title

Concurrent and legacy economic and environmental impacts from establishing a marine energy sector in Scotland

Authors

Grant J Allan[a,*], Ian Bryden[b], Peter G McGregor[a,c], Tim Stallard[d], J Kim Swales[a,c], Karen Turner[a] and Robin Wallace[b]

Affiliations

[a] Fraser of Allander Institute, Department of Economics, University of Strathclyde, 130 Rottenrow, Glasgow, G4 0GE, United Kingdom

[b] Institute for Energy Systems, School of Engineering and Electronics, University of Edinburgh, The King's Buildings, Mayfield Road, Edinburgh, EH9 3JL

[c] Centre for Public Policy for the Regions, Universities of Glasgow and Strathclyde, United Kingdom

[d] Joule Centre, School of Mechanical, Aerospace and Civil Engineering, Pariser Building, University of Manchester, M60 1QD, United Kingdom

Corresponding author

E-mail address: grant.j.allan@strath.ac.uk (Grant Allan)

Telephone: +44 (0)141 548 3838

Fax: +44 (0)141 548 5776

Abstract

We examine the economic and environmental impact that the installation of 3GW of marine energy capacity would have on Scotland. This is not a forecast, but a projection of the likely effects of meeting the Scottish Government's targets for renewable energy through the development of a marine energy sector. Energy, with a particular focus on renewables, is seen by the Scottish Government as a "key sector", with high growth potential and the capacity to boost productivity (Scottish Government, 2007a, p. 40). The key nature of this sector has seen targets established for renewable energy, to achieve environmental and economic benefits. Using a regional computable general equilibrium (CGE) model of Scotland we show that the development of a marine energy sector can have substantial impacts on GDP and employment over the lifetime of the devices, given encouragement of strong indigenous inter-industry linkages. Furthermore, there are also substantial "legacy" effects that persist well beyond the design life of the devices.

Keywords:

Wave energy, Computable General Equilibrium, economic impacts

Acknowledgements:

The authors gratefully acknowledge support from the Engineering and Physical Sciences Research Council through SuperGen Marine Energy Research consortium (grant references: GR/S26958/01 and EP/E040136/1). The authors are very grateful for detailed and extensive comments to an anonymous referee and to Scott Couch and Henry Jeffrey, University of Edinburgh, as well as to participants in: the World Renewable Energy Congress IX, Florence (August 2006); Regional Science Association International – British and Irish Section, Jersey (August 2006); CPPR-EUREAL Workshop, Glasgow (September 2006), the Mega-Projects and Regional Development workshop (CRETT, University of Bocconi, Milan, June 2007) and the North American Regional Science Association Savannah (November, 2007).

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 market[1].

In Scotland the situation is similar to that in the UK (Allan *et al*., 2007a; Royal Society of Edinburgh, 2006) in that all the existing major electricity generation facilities in Scotland could be closed within twenty-five years (RSE, 2006). The coal-, nuclear- and gas-powered electricity generation facilities in Scotland in 2000 had a total direct employment of 1,797 (full-time equivalent (FTE) jobs) (Allan *et al*., 2007a) and were indirectly supporting 10,035 FTE jobs in Scotland. At present, more electricity is produced in Scotland than consumed domestically, with roughly 20 per cent of the electricity generated in the region exported to the rest of the UK.

While energy supply decisions are strictly a matter reserved for the UK Parliament, the Scottish Executive has responsibility for energy efficiency and encouraging renewable energy development, and has recently (November 2007) announced an increase in already ambitious targets for renewable generation. These targets are to provide 31% of the electricity generated in Scotland by 2011 and 50% by 2020 from renewable sources (Scottish Government, 2007)[2]. Expressed in absolute terms, the Scottish Executive's (2005a) had accepted the Forum for Renewable Energy Development in Scotland's (FREDS, 2005) recommendation that their previous 2020 target of 40% (Scottish Executive, 2003) was consistent with an installed capacity of renewables of 6GW. It has been estimated that the revised 50% target would be consistent with an installed capacity of 8GW (Scottish Renewables, 2007). This requires substantial growth in renewables capacity given that present renewables capacity is 2.8GW[3] and presents opportunities for job creation. The Scottish Government recently announced that energy, with a particular focus on renewables, is a "key sector" for economic development, offering the potential for high growth and productivity increases (Scottish Government, 2007a). The previous Scottish Executive's Marine Energy Group (Scottish Executive, 2004) concluded that by 2020, a marine energy sector in Scotland providing 10% of Scotland's electricity production would be responsible for the creation of 7000 direct jobs, a considerable underestimate of potential total employment effects given the results we report below. The Scottish Executive's "Green Jobs" strategy (Scottish Executive, 2005b) identified renewable energy as one key area where Scotland could aim to be at the centre of the development and manufacture of new renewable technologies, particularly marine (p.8).

The additional 5.2GW capacity required to meet the Scottish Government new targets (given current capacity) is intended to come from a range of sources, and no specific targets have been set for the maximum contribution made by each type of renewable technology. However the Scottish Executive has launched a consultation to determine how the Renewable Obligations (Scotland) could be amended to support generation of electricity from marine (i.e. wave and tidal) resources (Scottish Executive, 2006, and see below for further discussion)[4]. Boehme *et al*. (2006, p. 52) show that for Scotland in 2020, after applying constraints concerning resource availability, economic viability and technological feasibility, wave power could contribute an installed renewables capacity in excess of 3GW, providing, on average, around 20% of the electricity demand in Scotland. Wave energy devices are currently closer to economic costs of generation, and scenarios for the medium term future of the portfolio of electricity generation (e.g. Ault *et al*., 2006) predict wave power playing a role. In this paper, the focus is thus on wave energy devices. Taking the figures of Boehme *et al*. (2006) as a feasible future for medium-term installed wave capacity, in this paper we therefore address the economic and environmental impacts of the installation, operation and maintenance of 3GW capacity of wave energy on Scotland.

In Section 2 we provide the motivation for the focus of the current paper on the likely impact of a marine energy industry for the Scottish economy and environment and summarises our broad approach. Section 3 outlines the investment characteristics of the wave energy installation and operation expenditures, together with the details of the central case simulation used in the remainder of this paper. In Section 4 we outline the AMOSENVI CGE model of Scotland and in Section 5 we report the "central case" results. In Section 6 we report key findings from extensive sensitivity analysis. Section 7 offers conclusions and outlines the implications of these results for energy policy in Scotland and the UK.

2. Motivation for focussing on the impacts of marine energy on economic development and the environment in Scotland

We begin with a general discussion of the motivation for our work and then briefly outline the main features of the approach.

2.1 General motivation

Conventional economic analyses of new technologies for the production of electricity tend to focus on their commercial attractiveness as a private investment (e.g. Previsic *et al*., 2004). This involves assessment of the detailed private costs and benefits (revenues) associated with new investment in such technologies, and assessment of the commercial viability of the associated new investments through conventional discounted cash flow methods (Stallard and McCabe, 2007). UKERC has examined the empirical applications for levelised cost estimates in general (Heptonstall, 2007), and the results of comprehensive analyses of this type applied to new marine technologies have recently been reported, for instance, Carbon Trust (2006). The Carbon Trust (2006) conclude that the cost of offshore wave energy converters lies in a range between 22 and 25 p/kWh, although there is uncertainty due to difficulties in estimating device performance and operations and maintenance costs. Costs for tidal stream centre on the range 12-15 p/kWh[5]. Moving to examine future costs from marine energy devices, the Carbon Trust consider conceptual and practical design improvements, economies of scale and learning at all stages of the development process. They argue that tidal stream devices could become competitive under plausible assumptions regarding learning rates, while for wave energy converters “fast learning or a step change cost reduction is needed to make offshore wave energy converters cost competitive for reasonable amounts of investment” (p. 22).

These analyses have been conducted for a range of wave energy devices and locations, allowing for location-specific sea states. These contributions suggest that current wave technologies are not competitive with onshore wind or with other traditional electricity generating sources, and may require additional policy support to create the incentive for private sector investment. Furthermore, there is an awareness that there may be future upward pressures on the costs of providing electricity through renewables as a consequence of the need to transmit electricity from where it is generated, often peripheral sites in the case of marine renewables, to where demand is greatest, namely the major urban centres. The distances involved and the required network capacity may impose both higher connection costs and the expense of possibly major upgrades to the transmission infrastructure. Naturally, the way in which any additional infrastructure is financed may prove vital for the viability of renewables in general, and marine energy sources in particular.[6]

However, useful though these conventional microeconomic analyses of new marine technologies undoubtedly are, they are typically subject to a number of limitations that suggest a degree of caution is required in interpreting their conclusions. First, as authors of the various studies are clearly aware, the current unit costs of producing electricity from wave energy convertors are likely to be a misleading indicator of future costs in anything other than the very short term, as is implied by the extensive use of "learning curves" in respect of the introduction of new technologies, suggesting that unit costs tend to decline through time, initially fairly rapidly. (Carbon Trust, 2006) The experience of the onshore wind industry is indicative of the importance of rapid technological consolidation and growth[7], resulting in costs per megawatt decreasing from 20 p/kWh in the early 1980s, to below 3 p/kWh by 2005 (Carbon Trust, 2006).) Learning rates for wind differ over the time period and region considered, but an overall learning rate of 18%[8] has been identified (Carbon Trust, 2006). While this experience may not be directly applicable to marine, there is little doubt that marine technology-related unit costs will fall over the longer term.

Second, there is evidence that policy, at least in a Scottish context, is set to increase the support available to generation from wave and tidal technologies, for instance, through the Marine Supply Obligation at the Scottish level[9], but also through grants targeted at pre-commercial wave and tidal energy devices[10]. At the UK level, there are also plans to make amendments to the Renewable Obligation Certificates, such as introducing "banding", and thus remove the current technology-blind nature of the ROC mechanism.

Third, a knowledge of the unit costs of electricity produced by any renewable source is, in general, insufficient to allow a proper assessment of their impact on total generating costs. There is a potentially very significant positive influence on the electricity generation system, namely the likely risk-reducing characteristics of renewables. In particular, renewables are not sensitive to the price of oil in the way that many other generation technologies are (Awerbuch, 2000; Awerbuch *et al*. 2006). The true additional cost of renewable electricity to the overall generating system may therefore be significantly less than the simple p/kWh estimates of renewable technologies. Of course, there are other important sources of risk, including variation in revenues that would be associated with the intermittency of renewables, but the absence of correlation with the oil price is clearly an advantage for an additional component to the overall generation portfolio, although it is one that is likely to be common to most, if not all, renewable energy sources.

Fourth, security of supply is a further dimension of energy system risk. Indigenously generated energy sources that are not critically dependent on imported inputs improve security of supply, though this is not a benefit that conventional microeconomic analyses of private costs and benefits would identify The increased security of supply generated through increasing the renewables element of generating capacity (or any other means) is an external benefit that would not be valued in any analysis of private costs and benefits. It would however, be incorporated into a social cost-benefit-analysis (CBA) which seeks to identify and evaluate *all* costs and benefits, i.e. including any externalities that will not be incorporated in estimates of private financial costs and benefits. In this respect all renewables offer advantages relative to gas-based generation, but if security of supply is also enhanced by indigenous control of technology, then this may become a source of differentiation among renewables. Not surprisingly, the extent to which generation technology (including its backward linkages to supplying industries) is indigenous also proves to be an important characteristic when assessing the potential for stimulating economic development, which we turn to next.

Conventional analyses of the private costs and benefits associated with new technologies tend to be microeconomic and partial equilibrium in nature: they proceed on a *ceteris paribus* assumption that seems reasonable for investments of a modest scale. Yet the potential for stimulating economic development through encouragement of an industry grown around marine energy is emphasised in wider debates, in both a Scottish and a UK context, and as discussed above, renewable energy has recently been included in the Scottish Government's economic strategy (Scottish Government, 2007a) as a key sector for economic development. This may in part be reinforced by a fairly widespread perception that such opportunities were missed in the early stages of onshore wind development. Furthermore, the scale of investments envisaged here suggests that we are dealing, in effect, with a regional "mega-project", and that we would expect there to be perhaps substantial impacts on the host economy. This would suggest that there is a perception of market failure here, in that the market outcome alone will not meet economic development goals, and that government support, through setting the correct policy framework, can assist in aligning market and socially optimal outcomes.

Accommodating effects on the wider economy requires the substitution of a partial for a general equilibrium approach: the macroeconomic or system-wide effects cannot be captured by traditional investment appraisal methods, because the latter assume, in effect, that the investment being appraised has no such effects. From the perspective of microeconomic analyses, any system-wide effects are again externalities. However, these effects can be and are anticipated by policy makers and are the main motivation for the recent/ proposed changes in Scottish and UK policy to improve incentives to develop marine energy. As noted above, there are signs of a desire to facilitate the movement of marine energy down a learning curve to become more competitive with other technologies, and this at least partially reflects the perceived prospects for future economic development.

Finally, an assessment of commercial viability of new technologies would typically not fully incorporate any beneficial environmental impacts, unless these are converted into private benefits, as they would be, at least in principle, under carbon trading schemes. In the absence of perfectly operating carbon trading markets, the costs of carbon-intensive generation technologies are not fully reflected in commercial investment appraisals, and their private cost may be substantially below their true social cost. Such concerns presumably underlie governments' overall reactions to climate change in general, and the adoption of the UK and Scottish targets for the proportion of electricity generation supplied by renewable sources that we have already identified. Of course, such targets may be imperfect substitutes for carefully designed carbon tax or emissions trading schemes. In particular, the expression of targets alone might be regarded as aspirations, whereas carbon taxes and emission trading are policy instruments specifically targeted at climate change mitigation.

In the present analysis we do not attempt to forecast the development of marine energy in Scotland. Rather we explore what the consequences for economic development and the environment in Scotland would be if the balance of relevant forces, including, of course, public policy and technological change, were such as to facilitate deployment of marine energy converters in a pattern similar to that for onshore wind, in order to satisfy the renewable energy targets of the Scottish Government. The purpose is to identify the potential of a marine energy industry to stimulate economic development in Scotland and to improve its environment through the reduction of greenhouse gases. While our analysis therefore stops short of a full cost benefit analysis[11], we do provide the first estimates of the likely system-wide impact of the development of marine energy on the economy and the environment of Scotland.

2.2 Outline of our modelling approach

Clearly, substantial expenditure is required to create the 3 GW of additional generation capacity in Scotland required to meet the Scottish Government's renewable energy targets through the installation of marine energy devices in Scotland. The economic impacts of these expenditures, from construction and installation to operation and maintenance, could be significant, particularly on a small regional economy like Scotland: indeed, as we have already noted, the scale of the investment relative to the host region suggests it should indeed be regarded as a regional mega-project. Input-output (IO) analysis, (originating with Leontief, 1941; see Miller and Blair (1985) for a review) continues to be the most widely employed method of assessing the impact of major new expenditures on regional economies in general and the impacts of expenditures in establishing renewable energy capacity in particular (Arthur D. Little, 2005; O'Herlihy and Co, 2006; Flynn and Carey, 2007; Lehr et *al*., 2008). However, this approach assumes that the region is characterised by substantial excess capacity and involuntary unemployment so that the regional economy can expand without putting any upward pressure on wages and prices (and the supply side of the economy therefore reacts passively to changes in demand).

The IO assumption of a passively reacting supply side sits uneasily with the recent, low-unemployment experience of the Scottish economy. Realistically, any stimulus to demand for Scottish goods, such as that associated with a major investment in renewables capacity, would initially be expected to put upward pressure on the demand for labour and Scottish wages and prices, reducing competitiveness and therefore Scottish exports. Such pressures would be expected to be mitigated in the longer-run, however, as higher wages and lower unemployment rates attract in-migration and capital accumulation. The limitations of IO assumptions are all the more apparent when, as here, the analysis focuses on the impact of a "mega-project"; that is a project that is large relative to the host economy. Such projects would be expected to exert a noticeable impact on the aggregate labour market and therefore on wages and prices[12].

Some recent work (Hillebrand *et al*., 2006), uses an econometric model to quantify the net impact the positive and negative impacts of subsidised additional investments in power generation technologies that accompany these compensation payments to renewable electricity producers. That paper argues that static and dynamic input-output models, with their use of average fixed coefficients and inability to take account of price changes, are unable to account for the "further indirect effects such as on tax revenue" (Hillebrand *et al*., 2006, p3485). Hillebrand *et al*. (2006, p3485) argues for the use of "a fully integrated model, which not only considers real (non-monetary variables) but also cost, price and budget effects". Our own approach employs a computable general equilibrium model (AMOSENVI)[13], which significantly generalises IO by incorporating a full specification of the supply side of the economy, and models relative price changes (including any impact on Scottish real wages) and their effects (including those on Scottish competitiveness). CGE models can converge on their IO equivalents, but only in circumstances where there is genuinely no scarcity of labour or capital (McGregor et al., 1996).

The CGE methodology has now become dominant in system-wide modelling of economic-energy-environment interactions and there are a rapidly growing number of applications to such issues at both national and regional levels. Since CGE models have a well-developed supply side (Allan *et al*., 2007b), they are well-suited to analysing the supply-side consequences of a series of capital expenditures such as that required to install and operate a target renewable generating capacity.

In this paper, we examine the economic and environmental impacts on Scotland of the installation and operation and maintenance of 3GW capacity of wave energy. Essentially we treat the generated electricity either as being exported to the rest of the UK or acting as a substitute for imported electricity. This would be consistent the renewable energy targets for Scotland being measured in terms of installed capacity, rather than the energy source of electricity consumed, in Scotland. We see that an investment in marine renewable generating capacity would create substantial economic impacts which persist long after the design life of the technology – "legacy effects". This legacy effect occurs even with low migration responses and rapid capital accumulation rates. This suggests that policy makers should look beyond the duration of direct expenditures when considering the economic and environmental impacts of mega-projects.

Of course, the counterfactual assumption is critical here, especially given the prospects of fairly radical changes in the composition of generating capacity in Scotland. That is, it is crucial to spell out what we are assuming would happen in the absence of the development of marine that is the focus of this paper. Given the uncertainties surrounding energy futures in the UK, we assume a counterfactual of "no change" other than the development of a marine energy sector. This allows us to isolate, in the simplest way, the changes that are attributable to marine *per se*. This is similar to the approach of Hillebrand *et al*. (2006) in which their scenario of increased renewable energy development is compared against a counterfactual which the "freezes the renewable energy status-quo". Naturally, the choice of counterfactual affects the interpretation of our results, and where this is especially important we provide some comparative discussion (without going into detail on alternative model simulations).

3. The central case scenario

Numerous wave energy devices are presently in development and several devices are now approaching commercial viability. In England, three developers have recently agreed terms for installation of a number of units at the WaveHub project in Cornwall (SWRDA, 2006). As mentioned earlier, nine wave and tidal projects have received financial support from the Scottish Government to fund testing of their device at the European Marine Energy Centre (EMEC) on Orkney. In this exercise we consider a single type of device, that of an articulated attenuator, which is the same device also considered by Boehme *et al*. (2006). It consists of four thirty-metre cylindrical steel sections joined together by three independent hydraulic power conversion modules (shown graphically in Figure 1). Each device has a total steel weight of 380 tons, a rated power output of 750kW and an average power output of 263kW.

[Figure 1: Schematic side view of single articulated attenuator-type wave energy device including primary components]

When deployed as part of a wave farm, multiple devices are installed in an array formation. As shown by Boehme *et al*. (2006) the average power generated by a device varies with device location but a mean capacity factor of 35% may be observed for 3GW of wave power installed in Scottish waters. 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. This is very similar to the deployment scenario for wave and tidal energy in the UK to 2020 published in the Marine Energy Challenge (BWEA, 2006).

[Figure 2: Cumulative total number of devices and annual number of devices installed, 2000 to 2020]

The assumed absolute and cumulative total number of devices installed at the end of each year is shown in Figure 2. 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[14]. The time periods over which installation, operation and refit activities occur are illustrated in Figure 3 and the costs associated with each expenditure phase are discussed in the following sections.

[Figure 3: Timetable of planned expenditures]

3.1 Installation expenditures

Figure 2 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 costs made each year as the discounted values of revenues, taking into account the electrical output generated by the devices operational during that year (kWh) and the 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* x average output (262kW) x 20 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 composition of costs between different expenditure categories. Each of these categories is then allocated to an appropriate Standard Industrial Classification and AMOSENVI[15] sector as described in Table 1 below. Note that the direct impact of installation is concentrated in two sectors, "Metal and non-metal goods" (sector 10) and "Transport and other machinery, electrical and instrument engineering" (sector 11), which receive 34% and 57% respectively of this expenditure.

Information on the imported content of these expenditures is uncertain, particularly given that we are considering future expenditures.[16] 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 concrete or steel structures). 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 plausible assumptions about the degree to which each component of capital expenditure is made within Scotland. These are given in column six of Table 1 and correspond to a Scottish share totalling 68.5% of the overall expenditure. We assume these proportions are fixed across all time periods of the simulation, so that, for example, the same percentage of total spend on undersea cables is made in Scotland in 2006 as in 2020.

The extent to which each component can be sourced from within Scotland significantly affects the economic impact felt by the region. 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 expenditures on the power conversion module 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.

3.2 Operating expenditures

Operating expenditures are small when compared to the capital costs for each device. However, these expenditures continue for the operating life of the device (here taken as 20 years) and so the total operating costs may be comparable to the capital cost. However, operating expenditures are difficult to predict as they include planned and unplanned maintenance and monitoring costs, all of which are sensitive to site location and device design. 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, in turn, 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 represent 51.9% of total expenditures over the design lifetime of the devices.

3.3 Refit expenditures

Ten years after installation, the devices must be removed from their site at sea for a complete overhaul and refit. This will include re-painting and 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). These 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 represent only 4.2% of total expenditure.

The time variation of the three Scottish expenditure elements: installation, operation and refit, are shown in Figure 4. Each expenditure stream includes all judgements regarding 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.

[Figure 4: Total annual expenditures in Scotland under central case scenario, £millions]

Notice that, in our central case scenario, we assume that the machines are decommissioned at the end of their working lives without replacement. This assumption is made simply to allow us to clarify the nature and scale of the legacy effects likely to be generated by such a mega-project. Recall, also, that we are focussing solely on the impacts of the new marine energy development: the counterfactual is of no change. As we noted earlier this is the simplest method of ensuring that all of the effects we identify are attributable directly to marine. We consider the significance of varying these two assumptions in the sensitivity analysis reported in Section 6.

4. Outline of model and simulation strategy

4.1 AMOSENVI model

To the extent that the significant expenditures associated with a marine energy industry are on goods and services produced in Scotland, aggregate demand in that region will be stimulated. Traditional economic impact studies would run these demand injections through a suitable input-output model for the national or regional economy in which these expenditures will be made. As we noted above, this approach makes the unrealistic assumption of significant excess capacity and involuntary unemployment, so that the supply side would adjust passively to demand with no upward pressure on wages or prices. However, in general, labour and capital are scarce resources and a stimulus to regional demand will put upward pressure on wages and prices, resulting in some loss of regional competitiveness. This implies that some Scottish exports that would otherwise have occurred are "crowded out" by price rises, limiting the rise in economic activity in Scotland. Our regional Computable General Equilibrium model for Scotland builds in relevant supply constraints and relative prices are determined within the model, adjusting so as to equalise the demand and supply for each commodity.

In a regional context the supply of labour services can vary through the migration of labour across regional boundaries, as well as in response to changes in participation rates. In AMOSENVI, the effective supply of indigenous labour increases with the real wage. Population, and labour supply, will increase if the net effect of migration into and out of the region is positive (so that inflows exceed outflows). Sectoral capital stocks include the physical plant and machinery that are a key input into the production process. They are only adjusted gradually in response to changes in sectoral profitability (the sectoral returns on capital).

The AMOSENVI model is explained in full in Hanley *et al*. (2006).[17] This is a variant of the AMOS Computable General Equilibrium (CGE) model of Scotland (Harrigan *et al*., 1991), developed specifically for investigation of environmental impacts.[18] 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 (oil, gas, coal and renewable and non-renewable electricity). These sectors are listed in Appendix 1. The model has three transactor groups – households, corporations and government; and two exogenous transactors – rest of the UK and rest of the world. Commodity markets are assumed to be competitive. We do not explicitly model financial flows, but make the assumption that Scotland has effectively no impact on UK interest rates, since it accounts for less than 10% of the UK economy.

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 producers seek to minimise costs in the context of a multi-level production function structure (common in CGEs), generally of a constant elasticity of substitution (CES) form, so that there is input substitution in response to the relative-price changes generated within the model. Leontief specifications, which allow no substitution between inputs (as is universally assumed in input-output analyses), are imposed at two levels of the hierarchy in each sector – production of the non-oil composite and the non-energy composite – because of the presence of zeros in the base year data on some inputs within these composites.

There are four components of final demand: consumption, investment, government expenditure and exports. Of these, real government expenditure is taken to be exogenous. Consumption is a linear function of real disposable income. Exports (and imports) are generally determined via an Armington link (Armington, 1969) and are therefore relative-price sensitive. How investment is determined in each period of the model is discussed below.

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). The regional real consumption wage is directly related to workers' bargaining power and therefore inversely related to the regional unemployment rate.

We run all the simulations below 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 both for the benchmark SAM dataset and where we have estimated behavioural relationships statistically. Within each period 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 which investment is equivalent to depreciation plus some fraction of the gap between the desired and actual capital stock of each sector. This process of capital accumulation is compatible with a simple theory of optimal firm behaviour given the assumption of quadratic adjustment costs.

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 based on the

Harris and Todaro (1970) model, which was estimated on UK data by Layard *et al*. (1991), 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 is assumed to have zero net migration in the base year and net migration flows re-establish this equilibrium. We shall see that the specification of the relevant elasticities in this regional migration function is a vital factor in the regional impact results of these simulations.

4.2 Simulation strategy

In each of the first thirty-five periods, the appropriate sectorally disaggregated installation, operation and refit expenditures are entered as stimuli to the demand side of the model, with the distribution of expenditures among sectors identified in Section 3 above. The model is then run forward for a further 65 periods with no additional exogenous shocks, so that the sole "disturbance" to the regional economy is the set of expenditures required to establish the 3GW capacity for marine energy. It is important to note again that we are not using AMOSENVI as 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 measured relative to a constant base scenario, so that all of the results are attributable to the direct or indirect effect of the positive demand disturbance associated with the establishment of marine energy. We explore the implications of alternative assumptions about the counterfactual in Section 5 below.

5. Central case scenario results

Recall that the central case scenario assumes that the machine energy convertors are decommissioned at the end of their lives without replacement (an assumption we relax in Section 6), to allow us to emphasise the significant timing differences between the expenditures and their impact on the Scottish economy and environment. As detailed above, Figure 3 shows the time pattern, while Figure 4 shows the total annual amounts, associated with these expenditure shocks. These expenditures represent the stimulus to aggregate demand in Scotland in each period. Figure 5 summarises the impact of these demand increases on Scottish GDP, as determined by simulation of 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, not all goes to Scottish GDP. Intermediate inputs produced outside of Scotland fail to contribute to Scottish GDP. Second, there is crowding out in some sectors as the expansion in demand (discussed in detail in Section 3) increases wages and commodity prices. This leads to a loss of competitiveness that reduces some Scottish exports and results in a fall in GDP in these sectors.

[Figure 5: Absolute difference in GDP from base and expenditures]

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 (in the assumed base case) 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 6: Absolute differences in employment and change in working population]

Figure 6 gives the simulation impacts on total employment generated by the introduction of the marine technology *per se* (since no other changes in generating capacity are incorporated into the base case simulation, though see Section 6 for a sensitivity analysis). 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.[19] Note that this is a change in population brought about solely through increased net migration only since we do not model "natural" demographic changes. This positive net migration is a response to the tightening of the labour market (i.e. increased demand stimulates increased demand for labour, pushing wages up). However, once the installation stage stops, the additional population (and work force) is a key factor in the subsequent legacy effects.

There are clear sectoral differences within this aggregate result which will reflect, among other things, the extent to which individual sectors are directly shocked by the demand injection and the sectoral links to other sectors. There will be crowding out of activity (i.e. in the short run, sectors compete for a fixed supply of capital and labour factors of production), away from sectors not directly affected by the demand stimulus, while sectors experiencing the demand injections will experience increased output (due to there offering higher returns to factors). Two key features of CGE models such as AMOSENVI are their generally high level of sectoral disaggregation and the active supply-side. Conventional macro-models have very limited sectoral disaggregation, whilst other sectorally disaggregated, but purely demand-driven, modelling approaches, such as standard Input-Output, cannot allow for crowding out effects.

Figure 7 and Figure 8 give the evolution of output change in what we refer to as the "stimulated" and "non-stimulated" sectors respectively. The stimulated sectors are those that received a direct exogenous demand stimulus as a result of the marine energy installation, operating and refit expenditures. Prices increase in these sectors, stimulating both output and also 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. Whilst there are potential positive indirect and induced demand effects, crowding out effects also occur, especially through the upward pressure on wages and prices that result from a tightening labour market.[20]

[Figure 7: Sectoral changes in output of stimulated sectors, % differences from base]

[Figure 8: Sectoral changes in output of non-stimulated sectors, % differences from base]

It is clear that the four sectors directly affected by the initial installation of marine energy devices, who are therefore the immediate recipients of a demand stimulus, experience the biggest individual year output changes. These sectors are "Metal and non-metal goods", "Transport and other machinery, electricity and instrument engineering", "Construction" and "Communications, finance and business". "Metal and non-metal goods" record a 10% increase over base-year values in 2020 as a result of the creation of marine energy capacity.

For sectors that are not directly affected by the installation expenditure, the output effects are more muted and initially more varied. Figure 8 shows that by 2020, the impact on the majority of these sectors is small but negative. Again there is a spike in output at 2020 with 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.

[Figure 9: Real and nominal wage values in central case, % differences from base]

As we have already argued, wage changes are a key factor in driving the output results for the non-directly stimulated sectors. The real and nominal wage changes are charted for the central case scenario in Figure 9. Both the real and nominal aggregate wage rates increase in the first phase, between 2006 and 2020, as the marine energy capacity is installed. In these periods significant exogenous expenditures (essentially up to 2030 when refit expenditures end), there is upward pressure on wages and thus prices so that some exports are crowded out in order to facilitate the increase in installation and refit activity. In the second phase, whilst operating and refitting continue, both the real and nominal wage initially decline so that in 2021 the real wage is slightly below and the nominal wage slightly above the base year level. Up to 2030, both real and nominal wages rise and both are above their base year levels at the end of this period. Between 2031 and 2040, as the operating expenditure gradually diminishes to zero, both nominal and real wage fall. Lower wages act as a stimulus to the Scottish economy and it is primarily this that produces the large legacy effects seen in Figure 5.

The environmental effects from the central case scenario in terms of increased pollution of CO_2 are shown in Figure 10. These show that there are very little differences in emissions of CO_2 small increase (less than 1% higher at their maximum). Note, however, that these are simply the resultant CO2 changes from the increased expenditures associated with installing and operating marine energy capacity, against an unchanging base case scenario. The assumed counterfactual proves crucial for assessing the environmental impact of marine energy, although this counterfactual should also take account of the lifecycle environmental impacts for each electricity generation technology, though such an analysis is beyond the scope of the present paper.

[Figure 10: CO2 emissions, % differences from base]

6. Sensitivity analysis

One advantage of using a CGE model to quantify the economic impact of these expenditures is that it is straightforward to test how sensitive the simulation results are to assumptions about model specification in general and functional forms or key parameters in particular. This is especially useful when performing *ex ante* scenario analysis as we are here. We have stressed in our central case scenario the 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. In the following sections, we investigate the extent to which our results are changed if we vary the responsiveness of, first, migration and, second, investment to changes in Scottish economic activity. Third, we consider alternative functional forms for the production structure. In particular, we remove the substitution possibilities and supply constraints from within the model and configure it as a standard demand driven dynamic Input-Output system. We compare the results from these simulations with those derived in our central case scenario in the following section. Fourth, since the legacy effects are in some cases important, we consider the impact of applying conventional "discounting" to these results, where the time value of gains receipts into the future are converted to their "present value" today. This is a standard technique where impacts are experienced over a long duration, and might have important consequences for the policy approach.

Fifth, our base case assumes that the investments are not renewed once the initial marine energy converters reach the end of their working lives, to allow us to emphasise the scale of legacy effects. It seems more likely that these would be continually replaced, a possibility we investigate in the next section of our sensitivity analysis. Finally, we consider the possible effect on our assessment of economic development and environmental impacts of an alternative counterfactual, in which the development of marine occurs as the capacity of other electricity generating sectors falls (possibly partly through policy-induced plant closures).

6.1 Varying migration sensitivity

One key characteristic of the central case scenario is the fact that increased wages and a lower unemployment rate in Scotland generate an influx of workers into Scotland (positive net migration). The inflow of workers that occurs eases supply constraints and continues to stimulate the supply side of the economy even when the flow of additional expenditures has ceased. These additions to the labour force are a major source of the legacy impacts that we have already observed. Here we quantify the impact of varying the strength of the migration effects. However, ultimately, as wages begin to fall, there is an outward movement of workers from Scotland.

The detailed specification of the migration equation used in the AMOSENVI model is given in Equation (1):

$$\text{(1)} \qquad \ln\left[\frac{m^S}{L^S}\right] = \varsigma - 0.08\left[\ln u^S - \ln u^R\right] + 0.06\left[\ln\left[\frac{w^S}{cpi^S}\right] - \ln\left[\frac{w^R}{cpi^R}\right]\right]$$

Where m is net migration to Scotland, w is the nominal wage, u is the unemployment rate, cpi is the consumer price index, L is population and ς is a constant, calibrated to ensure zero net migration (the equilibrium condition) for the base year data. The superscript S and R indicate Scotland and rest of the UK respectively. The default coefficients on the relative real wage and unemployment terms are w=-0.08 and u=0.06 respectively and are taken from econometric work reported in Layard et al (1991). We investigate the responsiveness of the central case results to variation of these coefficients. We report three cases: a "medium" scenario where we halve the coefficients in equation (1) to -0.04 and 0.03 respectively; a "low" scenario where the coefficients take the values -0.01 and 0.01 respectively; and a "zero migration" scenario where both coefficients are reduced to zero. The reason for looking at lower values is that if the expenditures associated with the installation, operation and maintenance of the marine devices are seen as temporary, the migration response might be more muted.

[Figure 11: Population in Scotland in central case and with medium and low migration elasticities, % differences from base]

Figure 11 shows the change in population under the various migration scenarios. Remember that in the "zero migration" case there will be no change in population – this would be represented by a line along the horizontal axis. Note that the larger the wage and unemployment coefficients, the more sensitive migration is to these economic factors and so: the bigger the maximum impact on population change; the sooner that this maximum impact is attained; and the faster the population effects subside.

[Figure 12: Absolute GDP impact for the central case against the medium, low and zero migration scenarios]

Figure 12 identifies the GDP changes under the various migration assumptions. The key point is the importance of migration for the size of the GDP effects. This is seen very clearly if we compare the figures from the "central case" and "zero migration" simulations. A lack of positive net migration limits the GDP impacts of the first phase where marine capacity is being installed. However, the impact is relatively small because the build up of expenditure is rapid. The real differences in the GDP impacts occur in the period after 2020 over which the population remains almost static for the central case, indicating that net migrants are retained, until 2030. The additional labour force also has important supply side impacts. In 2030, the GDP change over the base year value for the "zero migration" simulation is just over half of the value for the central case scenario. Further, from this point on, the ratio rapidly falls.

If we now match the central case simulation results with those for the medium and low migration coefficients, the comparison is less straightforward. As would be expected, for the period to 2020 lower migration coefficients result in smaller increases in population, and therefore also smaller increases in GDP and employment. This ranking of results for the main aggregate variables continues over the second and third periods, whilst direct operating and refit expenditures are still made. However, from period 2046 the population under the medium migration coefficients is greater than for the central case scenario and from 2049, GDP is higher too. A similar shift occurs in favour of the low migration coefficients around 2070. Within this range of parameter values, we thus see a larger "legacy" impact when we make migration 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 dampened.

6.2 Varying investment sensitivity

We know from the zero net migration simulations reported in the last section that there are some legacy impacts, even where population is fixed. In the AMOSENVI model these additional effects operate through changes in the capital stock. However, any given proportionate change in capital stock will have less of an effect on GDP than an equal proportionate change in employment. This is because the share of labour in GDP is much greater than the share of capital. Also, in the AMOSENVI model changes in capital stock are industry specific. Therefore the impact of a demand expansion focussed on specific industrial sectors will expand capacity in those sectors, but the capital stock in other sectors may only undergo small changes, or might even fall if these sectors are adversely affected by crowding out effects in labour or product markets.

[Figure 13: Percentage difference in capital stock in period 15 relative to base period]

As an example, Figure 13 shows the proportionate changes in capital stock, as against the base year values, for the AMOSENVI sectors in 2020. This is at the end of the period of accelerating installation activity. Note that the increase in capacity in the sectors directly receiving investment expenditures, and especially sector 10 “Metal and Non-Metal goods”, is sizeable. However, the impact on other sectors is small and in the majority of cases negative. Although the increase in the real wage would lead to some substitution of capital for labour, this is dominated by the fall in value added output in most sectors as a result of their loss of competitiveness and consequent crowding out of their exports.

[Figure 14: Absolute GDP impact for the central case and with high speed of capital adjustment]

Figure 14 shows the sensitivity of the GDP figures to changes in the investment speed of adjustment parameter. This is the proportional adjustment in each period to the difference between the actual and desired capital stock discussed in Section 4.1. The default value used in the central case simulation is 0.3. In Figure 14 we compare the central case results with those where the speed of adjustment parameter is increased to 0.5. As we expect, the GDP impacts in those periods where there are direct exogenous expenditures are greater for the more rapid capital adjustment. The economy responds more rapidly to reduce the capacity constraints generated by the demand injection. However, as with the migration results, the legacy impacts are increased where the adjustment speeds are lower.

6.3 Dynamic Input-Output

As we state in Section 4.1 in the AMOSENVI model production in each sector is modelled as a multi-level production function, where at most junctures the relationship is of a constant elasticity of substitution (CES) form. This makes the choice of inputs to production responsive to relative price changes, so that the rise in the wage, for example, will typically lead to some substitution of capital for labour in the production of value-added across all sectors. However, in the longer run this will also stimulate an influx of workers that tends to inhibit and ultimately reverse the rise in the wage. We also impose a fixed capital stock in each time period in the production of the sectors value added, and a wage determined through bargaining at the aggregate level. In this section of sensitivity analysis, we assume that supply responds passively to demand and we configure the model as an Input-Output system, albeit a fully dynamic version, augmented to accommodate migration effects.

The dynamic IO system is created by imposing fixed coefficients at all levels of the production functions, 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 without creating any upward pressure on wages and prices. The model thus becomes completely demand driven. We have also retained the investment function, so that, although output is not constrained by capacity in the short run, capital stock adjusts over time. We also retain the migration function, now solely driven by changes in the unemployment rates (since the real wage is now fixed). Thus, this simulation lets us see what a strict demand-driven, or IO approach, would quantify as the aggregate impacts of these expenditure injections.

[Figure 15: Absolute GDP impact for the central case and with Dynamic Input-Output system]

Figure 15 gives the time path for the change in GDP under our central case scenario on the same diagram as the Input-Output results. Note that with the IO model, the initial change is much greater: in 2020, the GDP change for the extended dynamic IO system is three times that given by the central case scenario. 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 that we observed in the base case. In 2020, the extended dynamic IO system gives an increase in GDP three times the value of that under the central case scenario.

However, by the same token, the IO model reacts strongly to the subsequent reductions in the exogenous expenditure associated with the introduction of the marine energy devices. For the period 2021 to 2030 the aggregate IO results are close to (but a little above) the AMOSENVI results. But after 2030 the IO model suggests a rapid decline in GDP, towards the base year value. After the operating expenditures finish in 2040 there is almost no activity change recorded by the IO model[21]. Contrast this with AMOSENVI's much more even path of GDP changes and extensive legacy effect that continue for another half century.

6.4 Present value of main aggregate impacts

In Figure 16 we sum the GDP effects over time for the simulations that we have discussed in this section. These results represent the sum of the increases in GDP that occur in each year that are generated by the development of the marine energy industry. We give the totals over the 100-year time period for which each simulation was run. We also break down that 100 years into 3 sub-periods: these are 2006-2020, the period where installation takes place; 2021-2040, when refitting and operational expenditures continue; and the period after 2040 when there are no further expenditure injections. We show the figures undiscounted and discounted for each of the main sensitivity simulations discussed so far. In each case, the undiscounted total is presented first, followed by the (inevitably smaller) discounted sum of GDP effects for the corresponding simulation. Where we discount, we follow the discount rate suggested by the Green Book (HM Treasury, 2003) in using a real discount rate of 3.5% for the first 30 periods, falling to 3.0% for the next 45 periods and then 2.5% from periods 76 to 100. This discount rate is intended to reflect social time preference, in that society will "prefer to receive goods and services sooner rather than later, and to defer costs to future generations" (HM Treasury, 2003).

Looking first at the undiscounted total effects, it is not only clear that the introduction of a marine energy sector in the Scottish economy would generate a significant stimulus to GDP, but also that this occurs over a long period of time. For example, the undiscounted central case scenario implies that, over the period, GDP would be a total of over £14billion higher than it otherwise would have been. Further, this result is insensitive to changes in migration and investment assumptions: the "medium" migration result is less than 2% lower and the high investment scenario total is less than 1% higher. However, the impact is clearly affected by larger changes in migration and the "zero migration" scenario simulation generates a total increase in GDP that is less than a half of the central case figure. Finally, the dynamic IO aggregate result is close to the central case outcome.

[Figure 16: Comparison of both GDP and discounted GDP impacts for central case and sensitivity simulations]

When we look at the discounted total effects in Figure 16 , the results change, not only in terms of their absolute size, but also in terms of the rankings of the different simulations. Discounting gives greater weight to the results in the earlier years so that simulations that deliver GDP impacts earlier are relatively favoured. This means that the present value of the GDP stream is maximised under the dynamic IO model. This is perhaps to be expected as in this model there are no supply constraints, and the response to the initial installation expenditures is strong but the legacy effects are minimal (and barely noticeable against the scale of Figure 16). The GDP benefits are very much loaded here towards the early period. However, the high investment simulation also gives a relatively large effect and the difference between the alternative migration simulations is magnified.

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 “zero migration” 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 (though not, of course, for the dynamic IO simulations). For example, in the central case scenario, discounted legacy effects make up just under 20% of the total discounted impacts.

6.5 The impact of a permanent expansion in the marine energy sector

Rather than decommissioning each device after it has served its expected twenty-year lifetime, the 3GW level of capacity may be maintained at this level indefinitely. Using the same expenditure assumptions for installation and operation and maintenance, we show in Figure 17 the equivalent diagram to Figure 4, but under the assumption that a pattern of installation, maintenance and then re-installation to replace the devices reaching the end of their design lifetimes. As before, these consist of three components: capital expenditures, which are repeated every 21 years to replace decommissioned devices; refit expenditures, which are incurred for each device after 10 years of operation; and ongoing operational expenditures, which remain constant at £403 million once the 3GW capacity (four thousand devices) is reached in 2020.

[Figure 17: Total annual expenditures in Scotland under central case scenario, with permanent expansion in marine energy sector]

The economic and employment impacts of these expenditures remain high after 2020 onwards as the decline in expenditures observed in Figure 4 is now replaced by a series of regular new installation of devices. These GDP impacts in the central case and the case with a permanent expenditure in the marine energy sector are shown in Figure 18 and Figure 19. There is no longer the declining pattern of "legacy effects", as described above, however the regular investments bring about increases in GDP which are well above those experienced with the central case scenario. The peaks of increases in GDP are observed in the years where demand expenditures are greatest (the top of the investment cycles). A similar pattern is observed for changes in Scottish employment..

[Figure 18: Absolute difference in GDP under central case scenario and with permanent expansion in marine energy sector, £millions]

[Figure 19: Absolute difference in employment under central case scenario and with permanent expansion in marine energy sector]

6.6 The likely effects of alternative counterfactuals

As the introduction to this paper makes clear there are significant uncertainties surrounding the future composition of electricity generation in Scotland and the UK. One possible approach to this problem is to take a range of possible energy futures without marine and then explore alternatives in which marine enters either to add to existing capacity or to replace carbon-based technologies or nuclear generation.

While this is undoubtedly worth exploring, the range of possibilities is such that this cannot be done without substantial additional research effort and further very extensive sensitivity analysis. However, research we have conducted on the impacts of alternative generating technologies is indicative of the likely differential effects on regional economic development associated with alternative technologies for generating electricity, although this research was conducted in an input-output framework (Allan *et al*., 2007a). This analysis suggests, for example, that the indigenous economic development potential of further expansion of onshore wind is rather limited, given that the technology is essentially imported, with modest assembly and maintenance expenditures impacting on the host region. Of course, this is not to deny the potential for local economic development associated, for example, with major wind farms located on island economies, although this is likely to be dependent on revenue-sharing agreements. Nonetheless, the potential impact on overall regional economic development in Scotland is likely to be much greater if government targets for electricity generation by renewables are met by an expansion of marine rather than further expansions of onshore wind.

Notice that here that it is not just the economic development effects that would be sensitive to alternative counterfactuals. Table 2 presents the environmental impacts of producing the peak marine electricity output (in the base case scenario) by alternative technologies. Peak marine electricity output for 3GW of installed capacity (4000 installed 750kW rated devices), assuming a 35% capacity factor is 9198 GWh. Replacing this electrical output from different generation technologies would create additional CO_2 pollution as shown in the final column of Table 2. Clearly, the biggest environmental "saving" is secured if marine replaces current coal generating capacity (unless new clean technologies are introduced)

[Table 2: Environmental impacts of producing peak marine electricity output by alternative technologies]

This brief discussion is, of course, subject to a number of limitations. First, the environmental impacts referred to above simply relate to the (foregone) production of greenhouse cases, once generating capacity is established. So, life cycle effects are not fully taken into account and this could have some impact on the scale of environmental gains. Second, the savings are merely indicative of orders of magnitude since we have not simulated the simultaneous decline of more traditional generating capacity simultaneously with the emergence of marine. This would limit, and possibly even offset, the upward pressure on wages and prices in Scotland, and so inhibit the degree of crowding out. However, the above estimates give a reasonable indication of the likely order of magnitude of environmental savings over the longer term.

7. Conclusions and policy implications

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 from wave and tidal technologies, as further R&D, industry learning and additional 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 industry sectors. In this paper we have sought to quantify the macroeconomic or system-wide impact that these expenditures could have on Scotland over the operating lifetime of 3GW capacity. Our use of a computable general equilibrium model allows us to relax the restrictive assumptions of input-output analysis, the traditional method of evaluating the regional impact of such developments, and accommodate effects on the competitiveness of the host region, including factor substitution effects in response to relative price changes.

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 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 can only be realised through additional learning and policy incentive effects. 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 breakdown of industry sector expenditures would be required to model the economic impact of other types of wave energy device or to account for the variation of installation and operating costs with site location. It may also be that the sector breakdown of expenditures would, in practice, vary with aggregate installed capacity due to differential learning between sectors. Clearly, the timing and duration of the impacts would depend upon the installation rate that is achieved, and might be different from that used here (and shown in Figure 1). Some scenarios for Great Britain show expected installed marine capacity reaching between 2 and 2.5GW in 2020 (Ault *et al*., 2006). The results presented in this paper could be scaled in line with the expected level of installed capacity.

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 have a beneficial environmental impact, in terms of reducing greenhouse gas emissions compared to gas and coal-based generation technologies, but will also stimulate Scottish economic development significantly, boosting Scottish GDP, employment and population. The scale of the stimulus to development will be greater the greater the degree of integration of the marine energy sector into the local economy: a greater proportion of locally sourced installation, operation and refit expenditures will lead to a greater positive impact on the Scottish economy. Where we have examined a hypothetical wave device in this paper, the methodology could be applied to the case of tidal technologies. There will be differences between alternative wave and tidal technologies, as the inputs to devices would vary. The impact of alternative devices could be explored through further sensitivity analysis, but in each case, for the regional economic impact, the backward linkages to the regional economy would be vital. Failure to establish a sufficient technical knowledge base in Scotland could result in the elements produced in Scotland consisting of only the low-value generic engineering components whilst the high value elements are imported. An examination of the linkages between onshore wind and the Scottish economy reveal these to be very limited, so that they do not provide anything like the same potential as marine for stimulating economic development in Scotland. The economic impact of meeting the Scottish Government's targets for the generation of electricity by renewables is therefore likely to be critically dependent on the composition of that renewables generating capacity.

Also, it is apparent that in appraising the likely impact of a mega-project in an open regional economy, it is important not only to consider the period over which the direct expenditures or activities related to that project are made, but also to look beyond that horizon to the longer term. An induced influx of labour and a stimulus to increased investment, made directly or indirectly in response to the project's expenditures, produce supply-side effects that can be very long lasting.

References

AEA Technology, 2006. The Scottish Energy Study, Volume 1: Energy in Scotland: Supply and Demand. Report published for the Scottish Executive, January 2006, available online at http://www.scotland.gov.uk/Resource/Doc/89792/0021573.pdf

Allan, G.J., Hanley, N., McGregor, P.G., Swales, J.K., Turner, K.R., 2006. The macroeconomic rebound effect and the UK economy. Final report to the Department of Environment Food and Rural Affairs.

Allan, G.J., McGregor, P.G., Swales, J.K., Turner, K.R., 2007a. The impact of different electricity generation technologies on the Scottish economy: an illustrative input-output analysis. Proceedings of the Institution of Mechanical Engineers, Part A, Journal of Power and Energy 221, 243-254.

Allan, G.J., Hanley, N., McGregor, P.G., Swales, J.K., Turner, K.R., 2007b. The impact of increased energy efficiency on the industrial use of energy: A computable general equilibrium analysis for the UK. Energy Economics 29, 779-798.

Armington, P. 1969. A theory of demand for products distinguished by place of production. IMF Staff Papers 16, 157-178.

Arthur D. Little Ltd, 2005. Wave Hub: Summary Business Case. South West of England Regional Development Agency

Ault, G., Elders, I., McDonald, J., Burt, G., Tumilty, R., 2006. Electricity network scenarios for 2020. paper for SuperGen Future Network Technologies Consortium. July 2006, ref: EPSRC/SGFNT/TR/2006-001.

Boehme, T., Taylor, J., Wallace, R., Bialek, J., 2006. Matching renewable electricity generation with demand: Academic study for the Scottish Executive by the University of Edinburgh. Scottish Executive.

British Wind Energy Association, 2006. The Path to Power: Delivering confidence in Britain's wave and tidal stream industry. Project report, June 2006 online at http://www.bwea.com/pdf/pathtopower/PathtoPower_low.pdf

The Carbon Trust, 2006. Future Marine Energy, Results of the Marine Energy Challenge: Cost competitiveness and growth of wave and tidal stream energy. The Carbon Trust.

Department for Trade and Industry, 2006. The Energy Challenge. HMSO, London.

European Commission, 2007. Renewables Obligation (Scotland) – amendment to an existing scheme. Letter to UK Government, 19th March 2007. Available online at: http://ec.europa.eu/community_law/state_aids/comp-2006/n851-06.pdf

Flynn, R.J., Carey, R.T., 2007. The potential economic impact of an off-shore wind farm to the state of South Carolina, The Strom Thurmond Institute.

Flyvbjerg, B., Bruzelius, N., Rothengatter, W., 2003. Megaprojects and risk: an anatomy of ambition. Cambridge University Press, Cambridge.

Forum for Renewable Energy Development in Scotland, 2005. Scotland's Renewable Energy Potential: realising the 2020 target. Scottish Executive, Edinburgh.

Hanley, N., McGregor, P.G., Swales, J.K., Turner, K.R., 2006. The impact of a stimulus to energy efficiency on the economy and the environment: a regional computable general equilibrium analysis. Renewable Energy 31, 161-171.

Harrigan, F., McGregor, P.G., Dourmashkin, N., Perman, R., Swales, J.K., Yin, Y.P., 1991. AMOS: A micro-macro model of Scotland. Economic Modelling 8, 424-479.

Harris, J.M., Todaro, M., 1970. Migration, unemployment and development: a two-sector analysis. American Economic Review 60, 126-142.

Heptonstall, P., 2007. A review of electricity unit cost estimates. Working Paper, December 2006, Updated May 2007. Report for UK Energy Research Centre, Reference: UKERC/WP/TPA/2007/006

Hillebrand, B., Butterman, H.G., Behringer, J.M., Bleuel, M., 2006. The expansion of renewable energies and employment effects in Germany. Energy Policy 34, 3848-3494.

HM Treasury, 2003. Green Book, Appraisal and Evaluation in Central Government. HM Treasury.

Layard, R., Nickell, S., Jackman, R., 1991. Unemployment – Macroeconomic Performance and the Labour Market. Oxford University Press, Oxford.

Lehr, U., Nitsch, J., Kratzat, M., Lutz, C., Edler, D., 2008. Renewable Energy and Employment in Germany, Energy Policy 36, 108-117.

Leontief, W., 1941. The Structure of the American Economy 1919-1929. Harvard University Press, Cambridge.

McGregor, P.G., Swales, J.K., Yin, Y.P., 1996. A long-run interpretation of regional Input-Output analysis. Journal of Regional Science 36 (3), 479-501.

Miller, R.E., Blair, P.D., 1985. Input-Output analysis: Foundations and extensions. Prentice Hall, New Jersey.

Morgan, J., 2007. Supporting Marine Renewables. Presentation to Scottish Renewables Marine Energy Seminar, 9th November 2007, Dundee.

Morimoto, R., Hope, C., 2004. Applying a cost-benefit analysis model to the Three Gorges project in China. Impact Assessment and Project Appraisal 22 (3), 205-220.

Ocean Power Delivery, 2006. World first wave farm – Shipping of first machine to Portugal. Press release 14th March 2006, online at http://www.oceanpd.com/docs/OPD%20ships%20first%20machine%20to%20Portugal.pdf

O'Herlihy and Co. Ltd, 2006. Wind farm construction: Economic impact appraisal. Final report to Scottish Enterprise. Scottish Enterprise.

Previsic, M., Bedard, R., Hagerman, G., Siddiqui, O., 2004. System level design, performance and costs for San Francisco Pelamis Offshore Wave Power Plant. report by Global Energy Partners, Electricity Innovation Institute and EPRI.

Royal Society of Edinburgh, 2006. RSE Committee of Inquiry into Energy Issue for Scotland, Final report, online at http://www.royalsoced.org.uk/enquiries/energy/full_report.pdf.

Scottish Executive, 2003. Securing a Renewable Future: Scotland's Renewable Energy. 2003. online at http://www.scotland.gov.uk/Resource/Doc/47034/0014765.pdf.

Scottish Executive, 2004. Harnessing Scotland's Marine Energy Potential: Marine Energy Group Report. Scottish Executive.

Scottish Executive, 2005a. Future of renewable energy mapped out. Press release 22nd July 2005, online at http://www.scotland.gov.uk/News/Releases/2005/07/22150102.

Scottish Executive, 2005b. Going for Green Growth: a Green Jobs Strategy for Scotland. Scottish Executive.

Scottish Executive, 2006. Consultation on Review of ROS (Support for Wave and Tidal Power) 2006. online at http://www.scotland.gov.uk/Resource/Doc/115084/0028289.pdf

Scottish Government, 2007a. The Government Economic Strategy. The Scottish Government, Edinburgh, November 2007.

Scottish Government, 2007b. Scottish Budget Spending Review 2007. The Scottish Government, Edinburgh, November 2007.

Scottish Renewables, 2007. Green electricity target grows by a third. Review: Issue 44, December 2007.

South West of England Regional Development Agency, 2006. Wave energy companies selected for Wave Hub. Press release 2nd February 2006, online at http://www.southwestrda.org.uk/news/release.asp?releaseid=1450.

Stallard, T.J., McCabe, A.P., 2007. MEC Quick Cost Calculator (Version 2), SuperGen Marine Energy Research Consortium Work Package 7 – Note 3, February 2007.

Appendix 1
The sectoral breakdown in the AMOSENVI model

		Industrial Order Classification
1	Agriculture	1
2	Forestry planting and logging	2.1, 2.2
3	Fishing	3.1
4	Fish farming	3.2
5	Other mining and quarrying	6,7
6	Oil and gas extraction	5
7	Food drink and tobacco	8 to 20
8	Textiles and clothing	21 to 30
9	Chemicals etc.	36 to 45
10	Metal and non-metal goods	46 to 61
11	Transport and other machinery, electrical and instrument engineering	62 to 80
12	Other manufacturing	31 to 34, 81 to 84
13	Water	87
14	Construction	88
15	Distribution	89 to 92
16	Transport	93 to 97
17	Communications, finance and business	98 to 107, 109 to 114
18	Research and development	108
19	Education	116
20	Public and other services	115, 117 to 123
	Energy	
21	Coal (extraction)	4
22	Oil (refining and distribution) and nuclear	35
23	Gas	36
	Electricity	85
24	Renewable (hydro and wind)	
25	Non-renewable (coal, nuclear and gas)	

Table 1
Installation expenditure categories, shares and industrial sectors

Expenditure category	*Expenditure share*	*Industrial sector*	*SIC*	*AMOSENVI sector*	*Scottish share*
Onshore transmission and grid upgrade	1%	Electric motors and generators	31	11	75%
Undersea cables	5%	Electric motors and generators	31	11	75%
Spread mooring	10%	Structural metal products	28.1	10	75%
Power conversion module	51%	Mechanical power transmission equipment	29.1	11	50%
Concrete structures	20%	Articles of concrete	26.6	10	95%
Construction facilities	4%	Structural metal products	28.1	10	95%
Installation	4%	Construction	45	14	95%
Construction management	5%	Architectural activities	74.2	17	90%
Total	100%				68.5%

Table 2
Environmental impacts of producing peak marine electricity output by alternative technologies

Technology	Electricity delivered (GWh)	Generation efficiency	Electricity produced	kg (CO_2)/kWh	CO_2 generated (Mt CO_2)
Coal	9198	37%	24860	0.30	7.5
Gas	9198	43%	21391	0.19	4.1
Nuclear	9198	37%	24860	0.00	0.0
Oil	9198	33%	27873	0.26	7.3

Notes: generation efficiencies and kg (CO2)/kWh figures for each technology taken from Table 12 in Scottish Energy Study Volume 1: Energy in Scotland, Supply and Demand (AEA Technology, 2006).

Captions to illustrations

Figure 1
Schematic side view of single Pelamis-type wave energy device including primary components

Figure 2
Cumulative total number of devices and annual number of devices installed, 2000 to 2020

Figure 3
Timetable of planned expenditures

Figure 4
Total annual expenditures in Scotland under central case scenario, £millions

Figure 5
Absolute differences in GDP from base and expenditures, £millions

Figure 6
Absolute differences in employment and change in working age population

Figure 7
Sectoral changes in output in stimulated sectors, % differences from base

Figure 8
Sectoral changes in output in non-stimulated sectors, % differences from base

Figure 9
Real and nominal wage values in central case, % change from base

Figure 10
CO_2 emissions, % differences from base

Figure 11
Population in Scotland in central case and with medium and low migration elasticities, percentage differences from base period

Figure 12
Absolute GDP impact for the central case against the medium, low and zero migration scenarios

Figure 13
Percentage difference in capital stock in period 15 relative to base period

Figure 14
Absolute GDP impact for the central case and with high speed of capital adjustment

Figure 15
Absolute GDP impact for the central case and with Dynamic Input-Output system

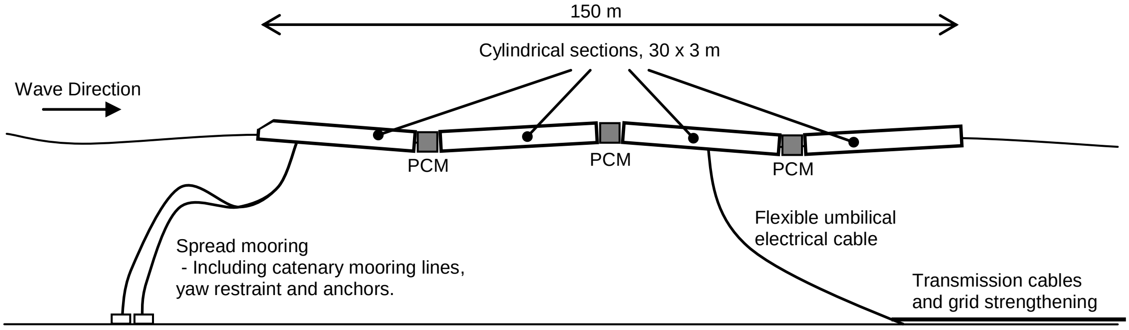
Figure 16
Comparison of both GDP and discounted GDP impacts for central case and sensitivity simulations

Figure 17
Total annual expenditures in Scotland under central case scenario, with permanent expansion in marine energy sector, £millions

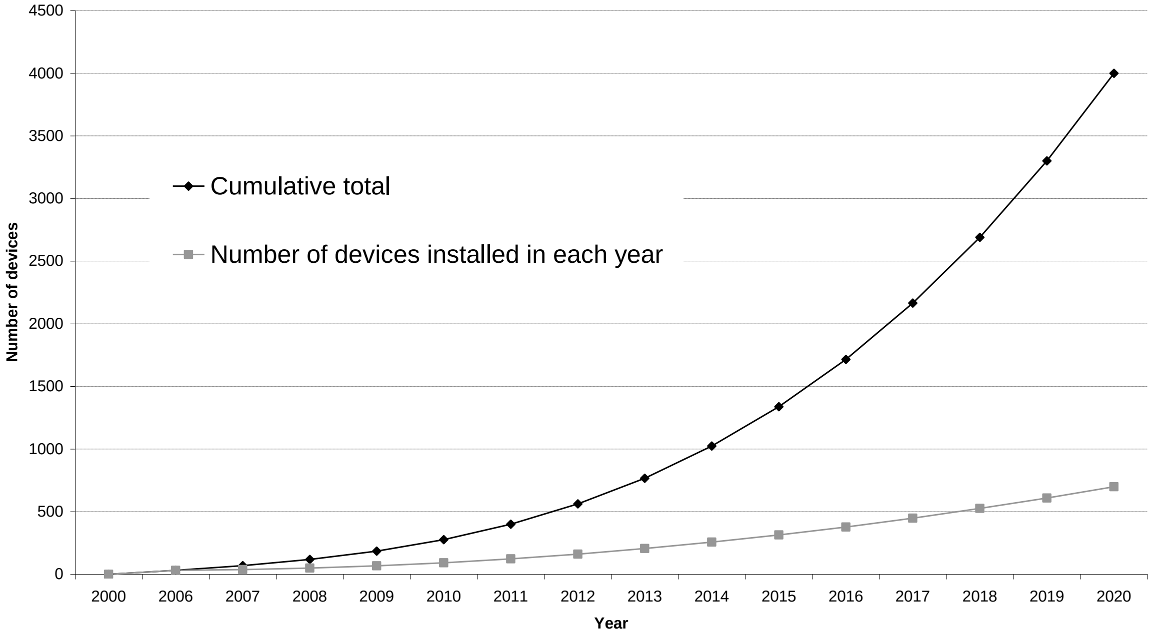
Figure 18
Absolute difference in GDP under central case scenario and with permanent expansion in marine energy sector, £millions

Figure 19

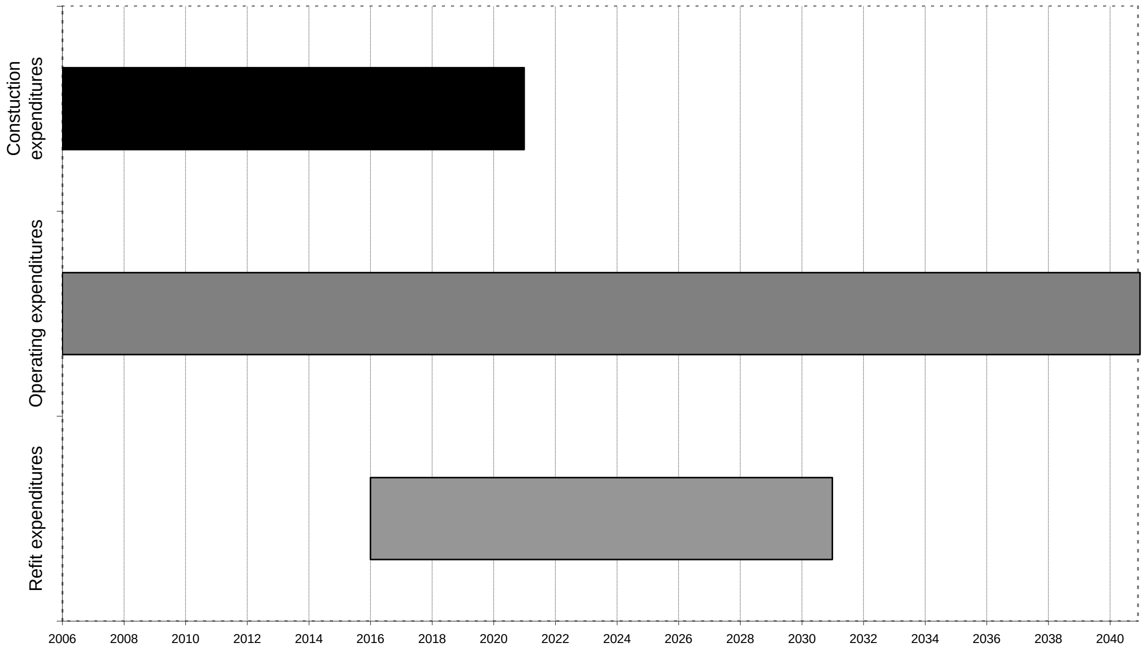
Absolute difference in employment under central case scenario and with permanent expansion in marine energy sector



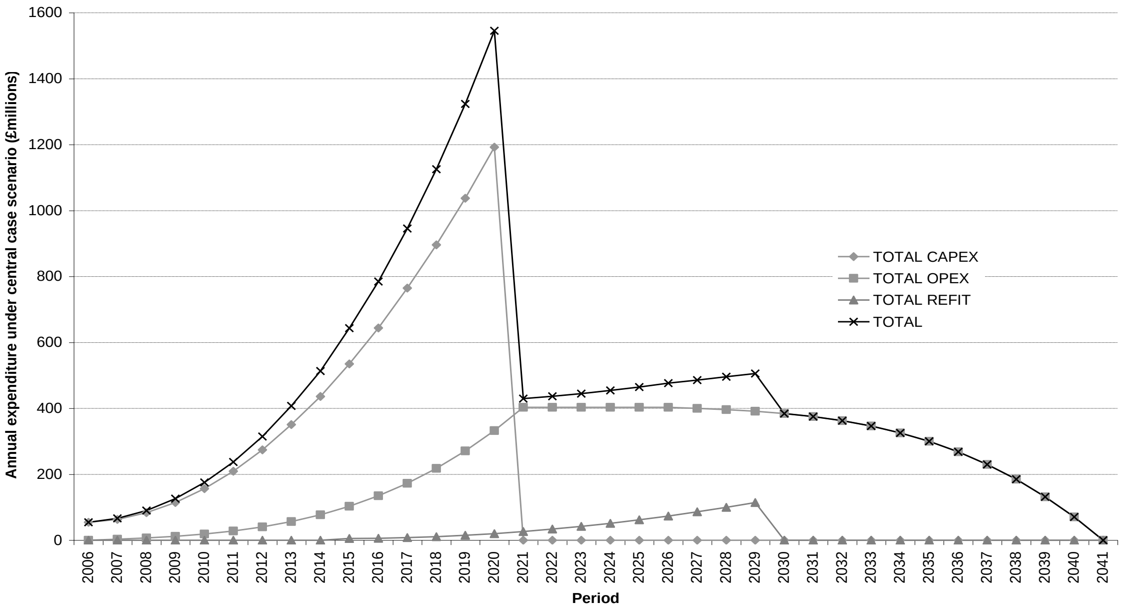
PCM: Power Conversion Module



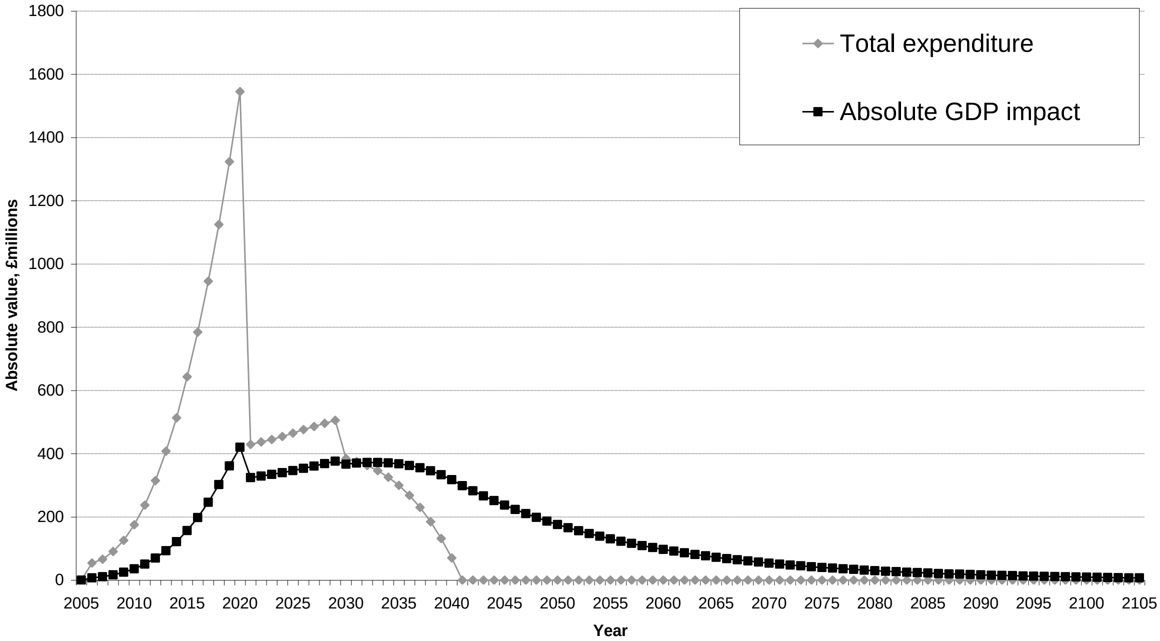
Cumulative total
Number of devices installed in each year
Number of devices
Year
0
500
1000
1500
2000
2500
3000
3500
4000
4500
2000
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

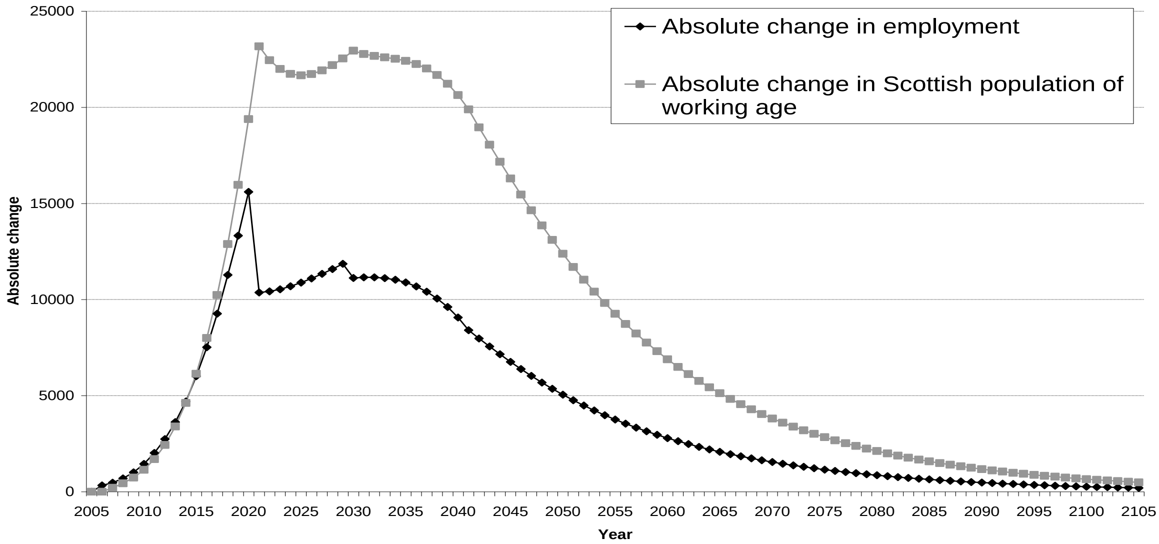


Constuction expenditures
Operating expenditures
Refit expenditures
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040

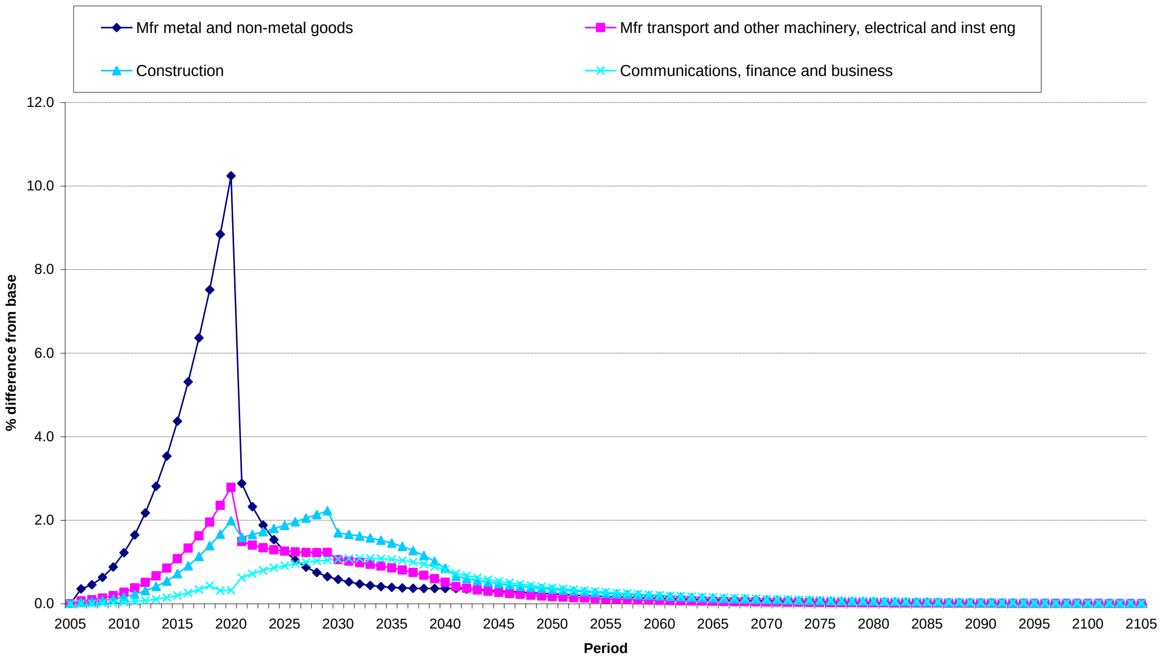


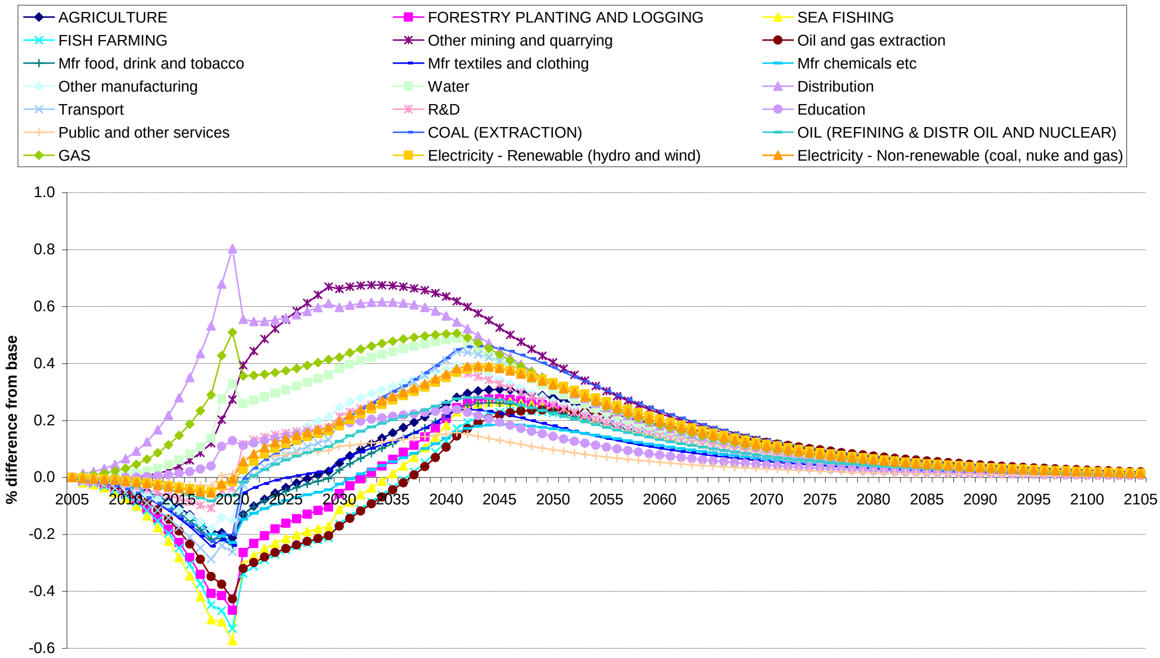
1600
1400
1200
1000
800
600
400
200
0
Annual expenditure under central case scenario (£millions)
TOTAL CAPEX
TOTAL OPEX
TOTAL REFIT
TOTAL
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
Period

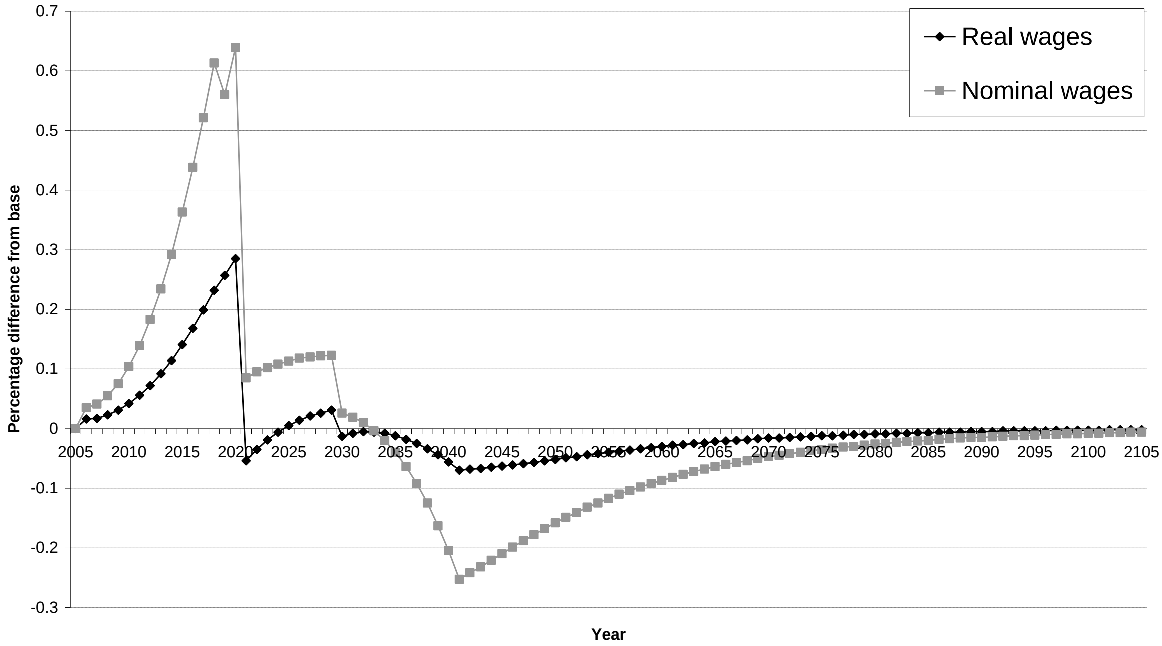

1800
1600
1400
1200
1000
800
600
400
200
0
Absolute value, £millions
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
Year
Total expenditure
Absolute GDP impact



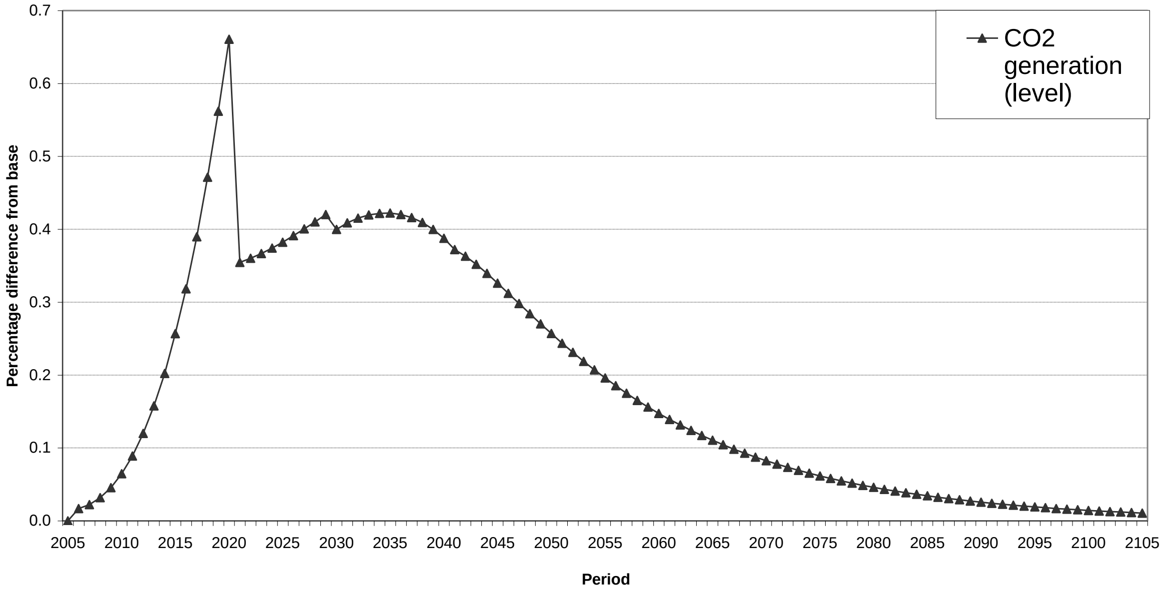
Absolute change in employment
Absolute change in Scottish population of working age
Absolute change
Year
25000
20000
15000
10000
5000
0
2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100 2105

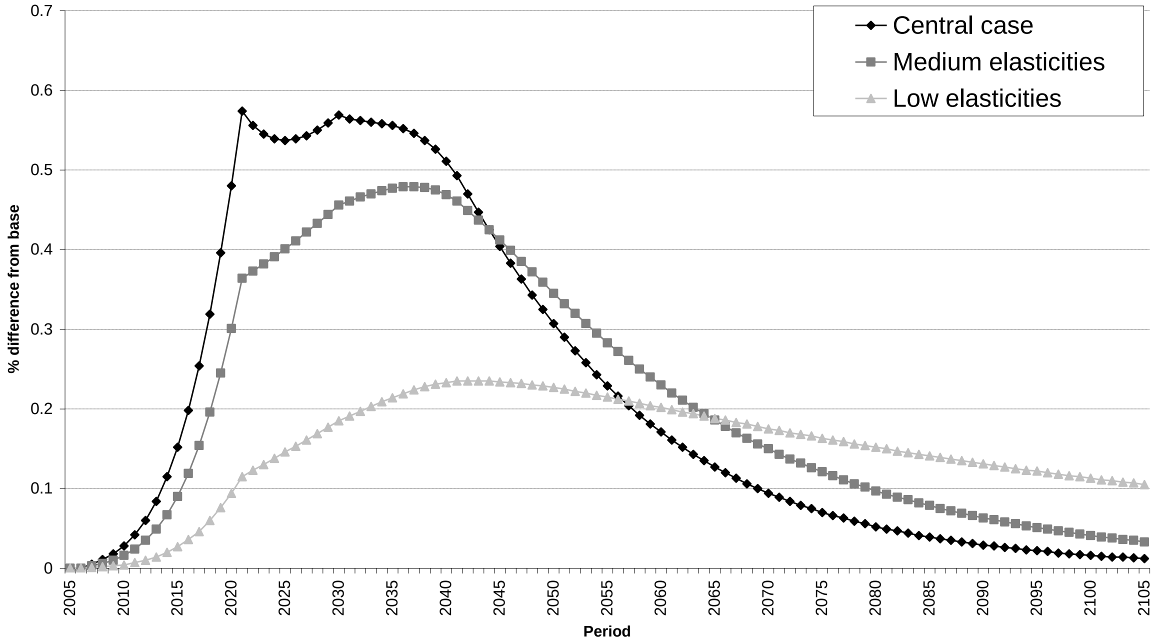

Mfr metal and non-metal goods
Mfr transport and other machinery, electrical and inst eng
Construction
Communications, finance and business
% difference from base
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
Period


AGRICULTURE
FORESTRY PLANTING AND LOGGING
SEA FISHING
FISH FARMING
Other mining and quarrying
Oil and gas extraction
Mfr food, drink and tobacco
Mfr textiles and clothing
Mfr chemicals etc
Other manufacturing
Water
Distribution
Transport
R&D
Education
Public and other services
COAL (EXTRACTION)
OIL (REFINING & DISTR OIL AND NUCLEAR)
GAS
Electricity - Renewable (hydro and wind)
Electricity - Non-renewable (coal, nuke and gas)
% difference from base
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105

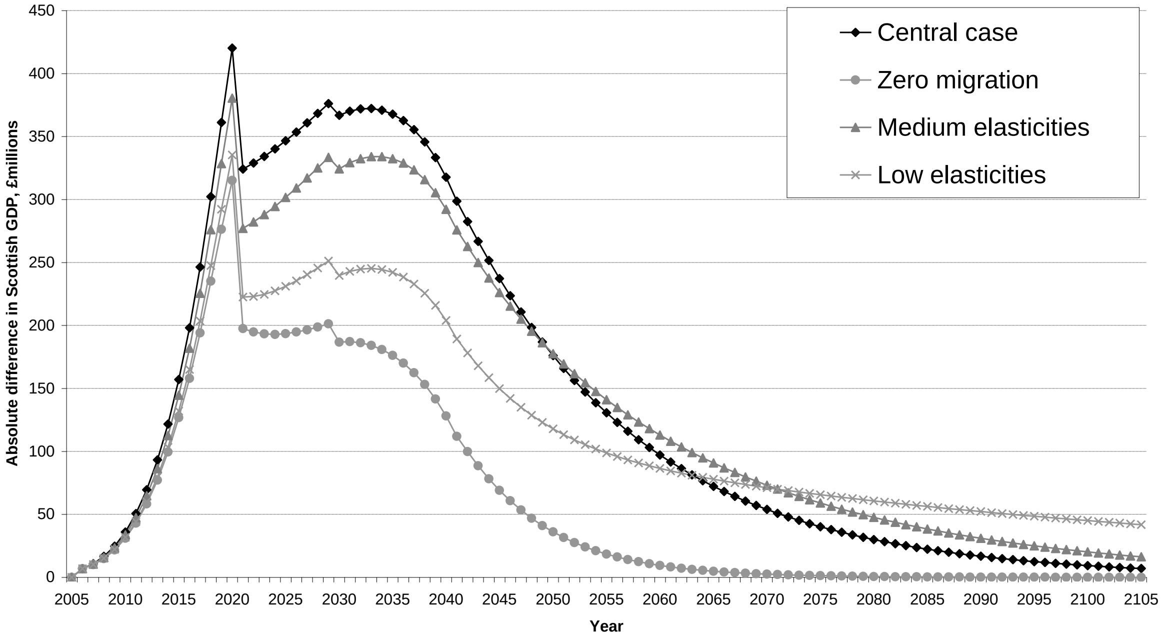


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Percentage difference from base
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
Year
Real wages
Nominal wages

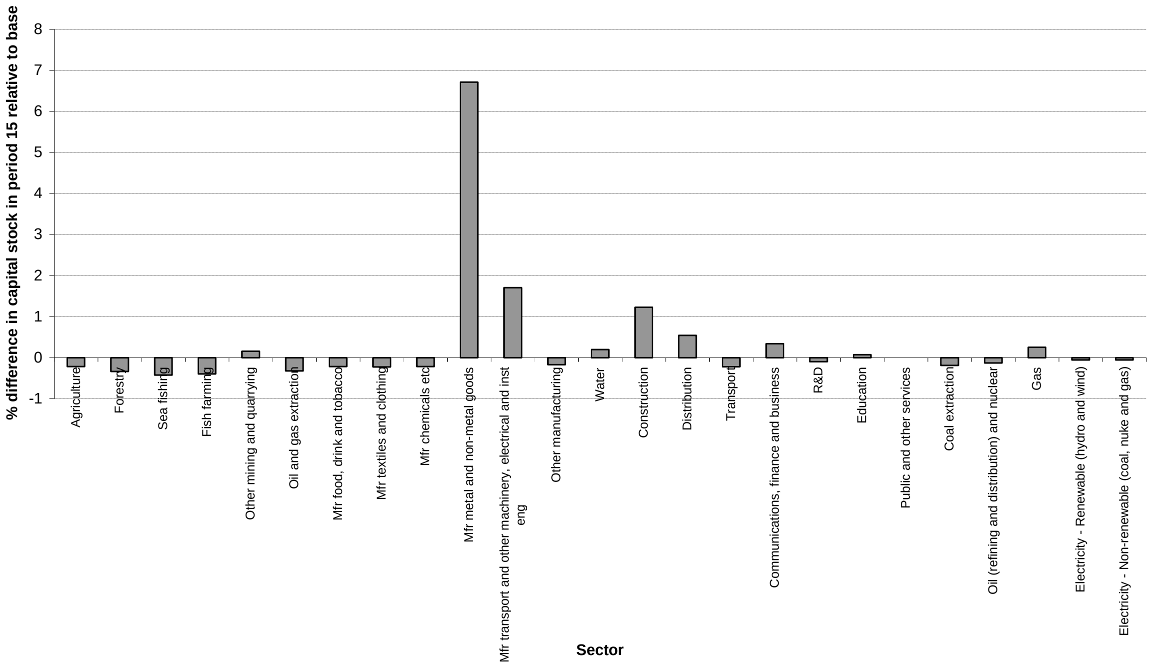

CO2 generation (level)
Percentage difference from base
Period
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105

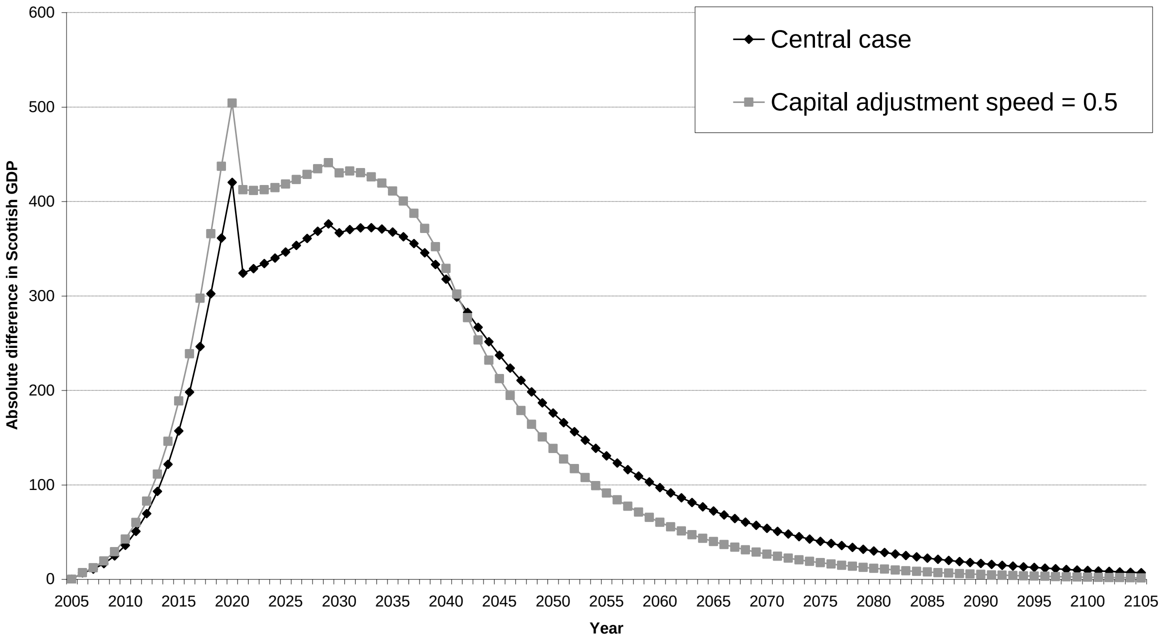


Central case
Medium elasticities
Low elasticities
% difference from base
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
Period

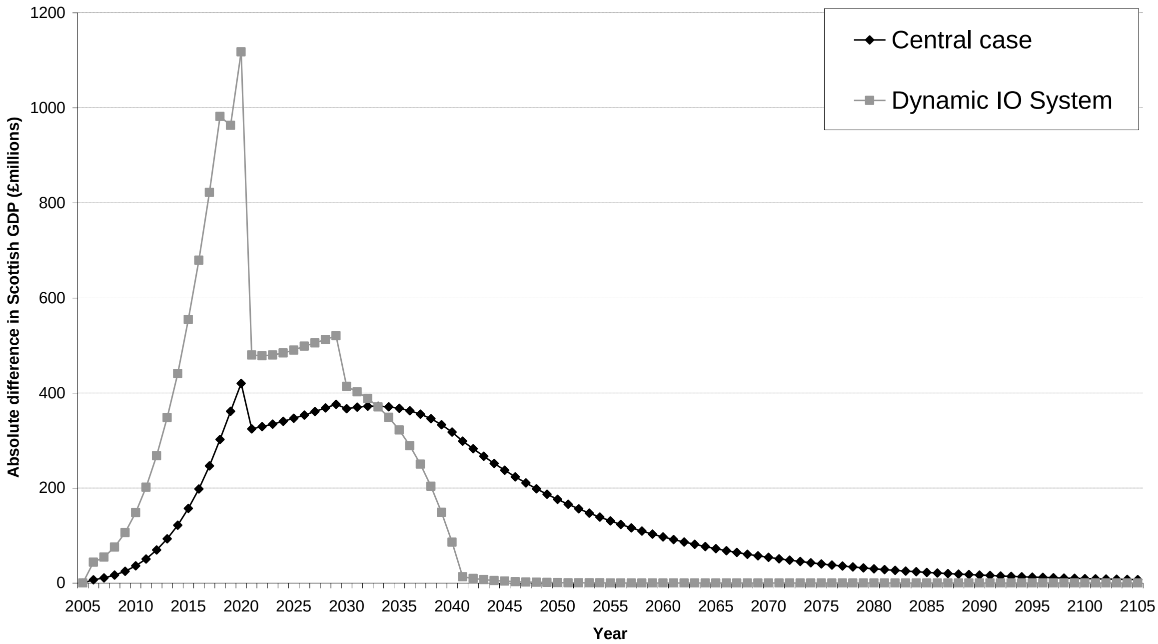


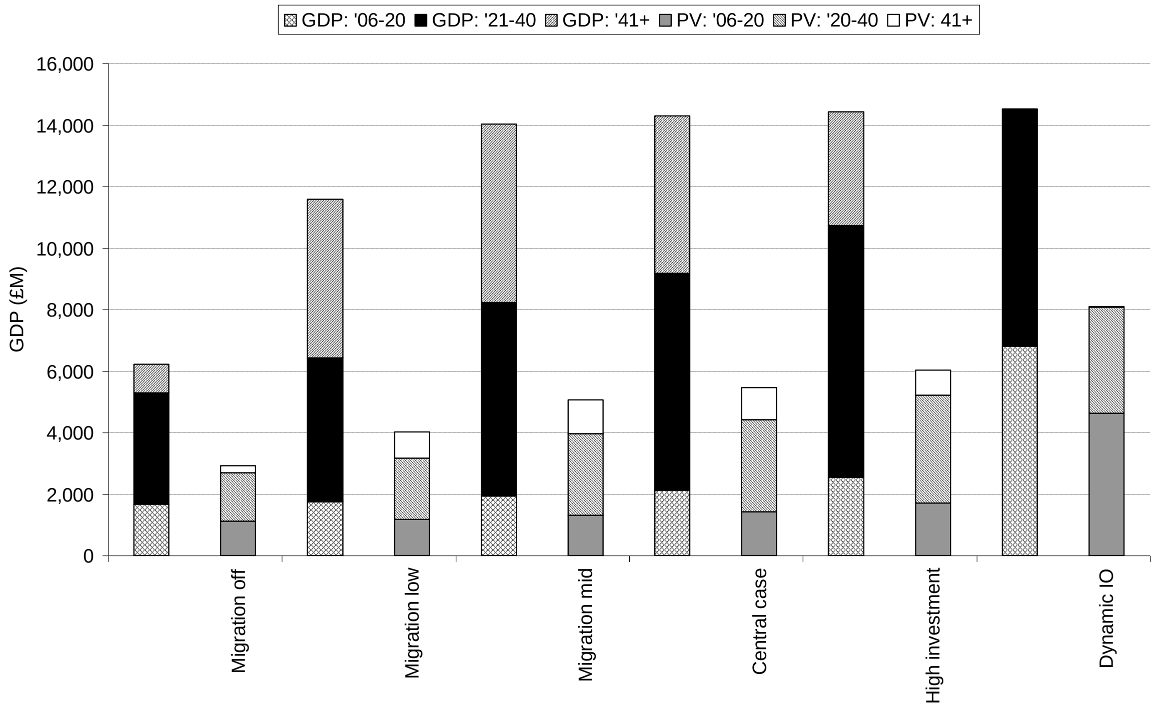
Central case
Zero migration
Medium elasticities
Low elasticities
Absolute difference in Scottish GDP, £millions
Year
0
50
100
150
200
250
300
350
400
450
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105

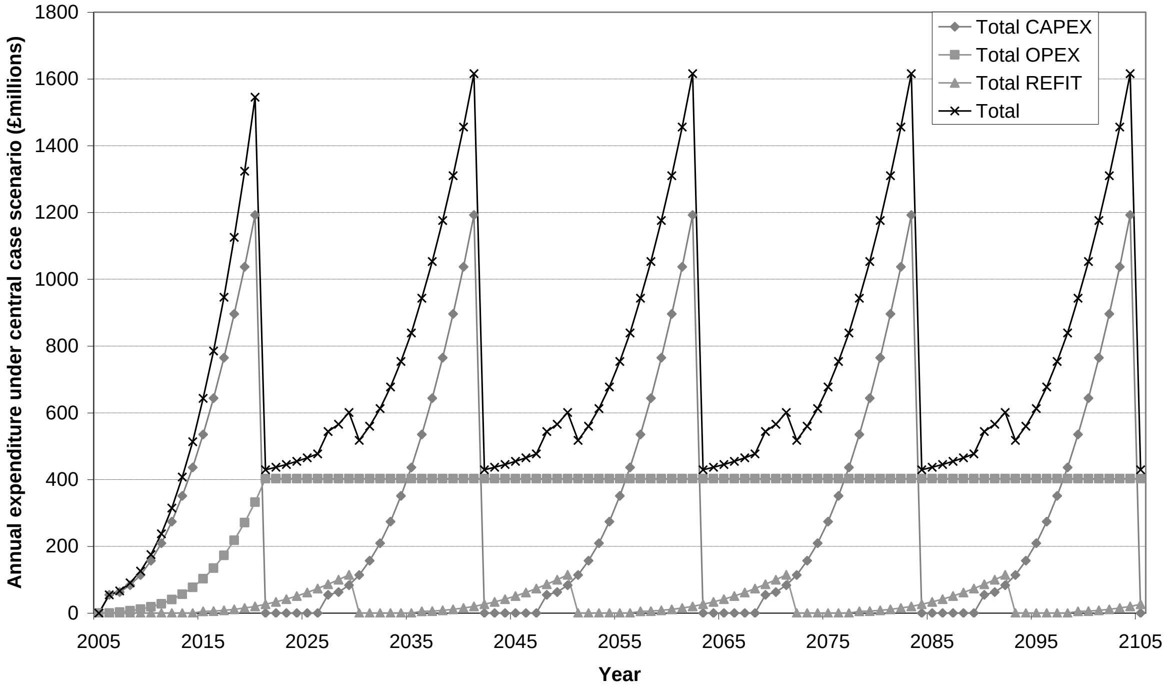

% difference in capital stock in period 15 relative to base
8
7
6
5
4
3
2
1
0
-1
Agriculture
Forestry
Sea fishing
Fish farming
Other mining and quarrying
Oil and gas extraction
Mfr food, drink and tobacco
Mfr textiles and clothing
Mfr chemicals etc
Mfr metal and non-metal goods
Mfr transport and other machinery, electrical and inst eng
Other manufacturing
Water
Construction
Distribution
Transport
Communications, finance and business
R&D
Education
Public and other services
Coal extraction
Oil (refining and distribution) and nuclear
Gas
Electricity - Renewable (hydro and wind)
Electricity - Non-renewable (coal, nuke and gas)
Sector

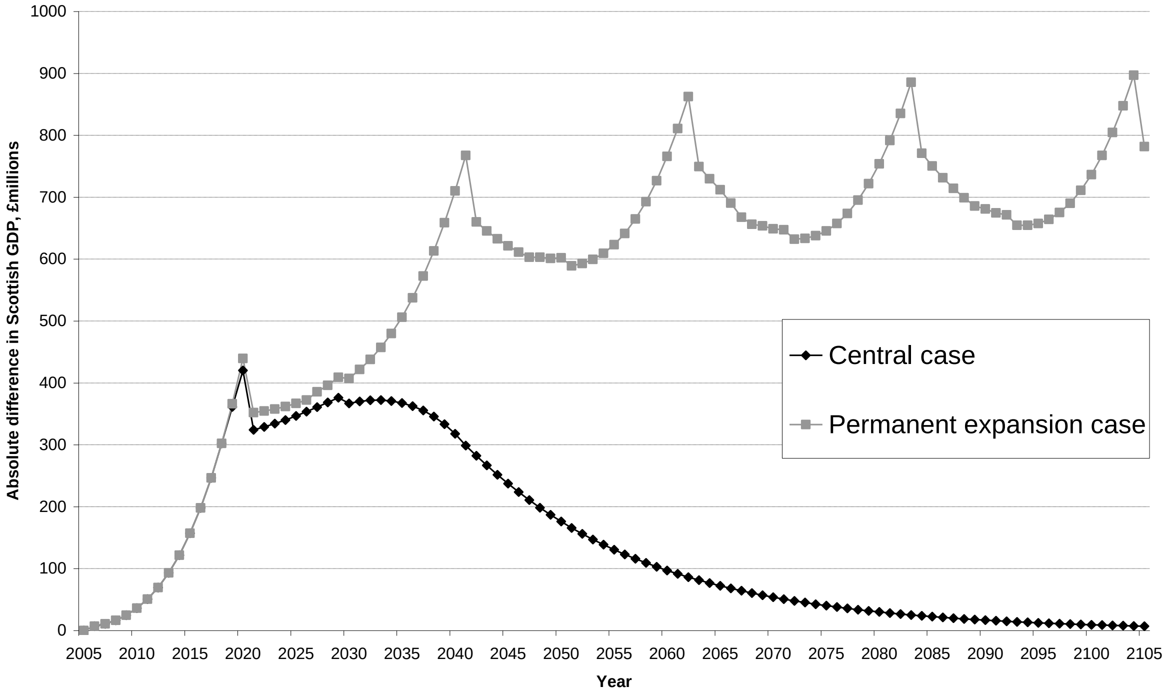


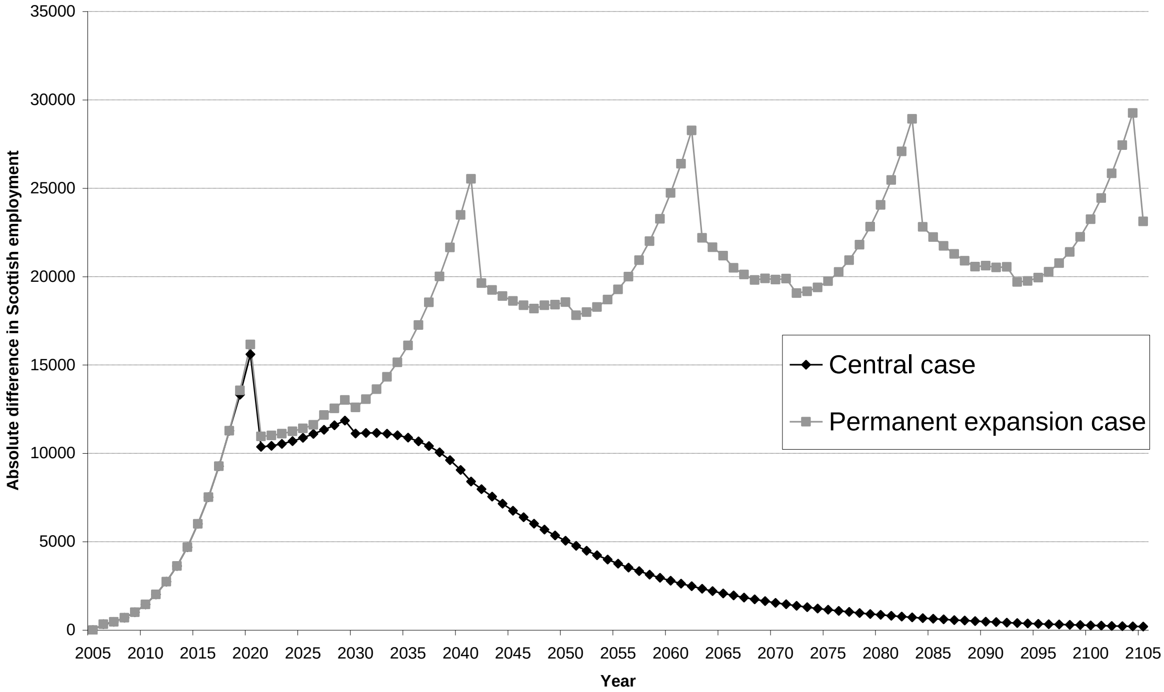
Central case
Capital adjustment speed = 0.5
Absolute difference in Scottish GDP
Year
0
100
200
300
400
500
600
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105


Central case
Dynamic IO System
Absolute difference in Scottish GDP (£millions)
Year
1200
1000
800
600
400
200
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105


GDP: '06-20
GDP: '21-40
GDP: '41+
PV: '06-20
PV: '20-40
PV: 41+
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
GDP (£M)
Migration off
Migration low
Migration mid
Central case
High investment
Dynamic IO


Annual expenditure under central case scenario (£millions)
Year
Total CAPEX
Total OPEX
Total REFIT
Total
0
200
400
600
800
1000
1200
1400
1600
1800
2005
2015
2025
2035
2045
2055
2065
2075
2085
2095
2105


Absolute difference in Scottish GDP, £millions
1000
900
800
700
600
500
400
300
200
100
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
2085
2090
2095
2100
2105
Year
Central case
Permanent expansion case


35000
30000
25000
20000
15000
10000
5000
0
Absolute difference in Scottish employment
2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100 2105
Year
Central case
Permanent expansion case

[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 to be installed in late-2007. 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)

[2] It was announced in early 2007 that the Scottish target for 2010 had been reached three years ahead of schedule. The UK has recently (October 2007) announced that it is unlikely to make its target for 20% of electricity to come from renewable sources by 2020.

[3] As of the end of November 2007.

[4] The recent Scottish Spending Review (November 2007, p. 13) has stated that the Scottish Government will provide financial and legislative support to realise 10MW of marine energy capacity by 2010. Additional support measures, such as the £8million Wave and Tidal Energy Support Scheme shows the Scottish Government continuing the work of the previous Scottish Executive in supporting marine energy.

[5] By way of comparison, from a survey of the literature on levelized cost estimates Hepstonstall (2007) reports that the mean of cost estimates for more established UK electricity generation technologies were as follows: coal = 3.29p/kWh, gas = 3.12 p/kWh, nuclear 3.22 p/kWh and wind = 3.19 p/kWh.

[6] Ofgem, tasked with the aim of promoting competition in the gas and electricity markets in the UK, have proposed a transmission charging regime based on encouraging generation near to sources of demand. This means greater transmission use of system charges for generators connected to the UK grid in Scotland, and particularly Northern Scotland. Speaking about the impact that this would have on renewable energy development in Scotland, Jim Mather, the Scottish Government's Energy Minister, in a statement to the Scottish Parliament (31st May 2007), said: "OFGFEM's approach to transmission charges is not helpful… I hope the UK Government will think again, that it will ensure that OFGEM takes more account of climate change objectives and, as a result, sets charging regimes which support rather than work against environmental objectives… The First Minister has already committed that we will work with companies here in Scotland to achieve that end. If it seems necessary we will press the UK government for a change to OFGEM's remit so more account is taken of medium term investment needs and of the case for investment in renewable technologies.

[7] Global installed capacity was 10MW in 1980, 2GW in 1990 and 50GW in 2005 (Carbon Trust, 2006).

[8] The learning rate is defined as the fraction of cost reduction per doubling of cumulative production.

[9] The Marine Supply Obligation (MSO) is designed to operate alongside the existing "technology-blind" Renewable Obligations Certificates (ROCS) which require electricity supply companies to provide certificates from accredited renewable electricity generation facilities for a growing share of their total sales of electricity. The MSO would provide extra support to wave and tidal sources by introducing an obligation on electricity suppliers in Scotland to source a fraction of their required Renewable Obligations Certificates from wave and tidal energy sources. The scheme starts in 2008, and is proposed to last until 2012. If the supplier does not meet the MSO level, it must pay the buyout price of £175/MWh for wave energy and £105/MWh for tidal energy. This compares to the existing ROC buy-out price, in 2005/6, of £33.24/MWh (European Commission, 2007).

[10] The Scottish Minister's Wave and Tidal Energy Scheme has provided £13 million, supporting, in total, nine wave and tidal projects with the costs of installation and deployment at the European Marine Energy Centre on Orkney (Morgan, 2007).

[11] Admittedly, many conventional CBAs are micro-oriented, but there is certainly no reason why they need be, and the present general equilibrium analysis would be an important input into such an analysis, especially when we are dealing, as here with the impact on the region of a mega-project.

[12] See Morimoto and Hope (2004) for a cost-benefit analysis of the Three Gorges project and Flyvberg et al. (2003) for a sober examination of recent mega-projects around the world.

[13] AMOSENVI is environmental version of AMOS, a macro-micro model of Scotland.

[14] A 20 year device lifetime, with a major refit after ten years, is also assumed in Previsic *et al.* (2004, p. 38).

[15] A detailed breakdown of the sectors in the AMOSENVI model is presented in Appendix 1.

[16] 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.*, 2007a).

[17] Allan *et al.* (2006) gives the UK national version of the model: UKENVI.

[18] AMOS is an acronym for a micro-macro model of Scotland.

[19] The working age population is taken here to be all those between the age of 16 and 64.

[20] Recall that the sole change in electricity generating capacity in the base case is the introduction of marine. Any reductions in nuclear and coal-generating capacity would exert a countervailing impact through the labour market that would at least limit, and possibly even offset, the tendency for crowding out effects to occur. See Section 6.6 for further discussion.

[21] The small effects observed are due to residual capital and population adjustments impacting on investment demand and consumption demand through household income.