Essays in the multi-sectoral economic modelling of energy technologies and policies

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Declaration of Authenticity and Author's Rights

This thesis is the result of the authors original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

Energy policy goals across many countries and regions seek to achieve multiple goals simultaneously, including to reduce emissions, improve energy security and enhance energy affordability. A further goal is that energy policy should make a positive contribution to economic development of the area, or that (at least) energy policy changes should not worsen economic outcomes. It is the contention of this thesis is that *ex ante* multi-sectoral economic modelling approaches – specifically, Input-Output (IO), Social Accounting Matrix (SAM) and Computable General Equilibrium (CGE) analysis – can usefully explore the potential economic and environmental consequences of energy technologies and policies. Specifically, these models can assist in identifying and quantifying the impact of policies on the competing goals of energy policy, and so improve the design of appropriate energy policy.

The thesis consists of six papers which apply multi-sectoral modelling approaches, all of which were published in peer-reviewed academic journals between 2007 and 2015 (inclusive). Each paper describes and/or extends multi-sectoral empirical economic analysis and modelling. The applications range from specific energy technologies – an onshore windfarm development, biofuels and developments in marine renewable energy technology – to potential energy policies – a (revenue-neutral) carbon tax and improvements in the efficiency of energy in production.

This thesis explores the fundamental characteristics, assumptions and uses of "fixed" and "flex-"price models. Working sequentially from IO and SAM to CGE methods, it explores the particular strengths, weaknesses and usefulness of each of these modelling approaches, and explains the contribution of the papers included in this PhD by published works to the academic literature and pertinent policy issues.

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1 Introduction

Energy policy across the world is being increasingly tailored to achieve multiple goals. The conventional "trilemma" of energy policy views the three objectives for energy policy as: reduce emissions – due to the connection between emissions from human activity and observed changes in the global climate – improve energy security and enhance energy affordability (for both industrial and domestic consumers). There is a natural tension between these objectives. Fundamentally, policy designed to meet one of the goals is likely to affect the progress towards the other goals. To these, a fourth objective has assumed an equal importance, which is that energy policy should make a positive contribution to economic development. The precise mechanisms through which developments in energy contribute to economic outcomes is a particular focus of the research in this thesis.

We can consider there perhaps to be three linked systems: the energy system (e.g. the transformation of energy resources to useful energy); the economic system - in which factors of production and inputs combine to produce goods and services for production and consumption; and the environmental system, from which resources are drawn and which is impacted by, for instance, emissions from the economic system. These systems are intrinsically interdependent: a disturbance to any one will impact on the others. Neglect of this interdependence can lead to policies having unanticipated effects.

There may be tension and perhaps even conflict among these goals. For example, replacing conventional electricity generation by renewables, could – under certain conditions – put pressure on affordability or economic growth. Therefore there is a need for decisions about energy technologies and energy policies to be guided by *ex ante* analysis of their likely impacts on the related energy, economy and environmental subsystems. A model which focuses on one of these systems would be unable to capture these critical interconnections between systems, necessitating the use of system-wide energy-economy-environmental models.

It is the contention of this thesis that *ex ante* multi-sectoral economic modelling approaches – specifically Input-Output (IO), Social Accounting Matrix (SAM) and Computable General Equilibrium (CGE) analysis – can usefully explore the likely consequences on energy, economic and environmental measures of energy technologies and policies. These modelling approaches are used in the papers contained in this PhD by published works to simultaneously capture energy, economy and environmental impacts. While the earlier papers in this PhD typically focus on the economy sub-system from a system-wide perspective, the modelling approach is applied to the complete energy-economy-environmental systems in later papers. Used sensibly, these models can assist the identification and quantify the impacts of developments in energy technologies and policies on energy policy goals. Additionally, through connecting the three different sub-systems, it is possible to identify the direction and scale of the trade-offs that are likely to exist among these goals.

Multi-sectoral economic modelling approaches can highlight a number of important elements. First, they identify the transmission mechanism between the technology or policy and the impact(s) of that intervention, e.g. the way in which one of the sub-systems is impacted by the policy choice. Second, they systematically model the processes through which an intervention in one sub-system impacts within that system, and in other sub-systems. Third, they identify the direction and scale of possible effects in each sub-system. Fourth, these approaches are all multi-sectoral in nature, and so can quantify impacts for different industries/sectors, as well as total (aggregate) results. For instance, there may be major differences in energy use or emissions by sectors, so that the composition of output (or changes in output) is critical for the impact on the stated goals of energy policies. Further, this means that analysis can describe the distribution of impacts, which might be crucial for policy[1].

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[1] For instance, the composition of electricity generation (the generation "mix") could be one measure of electricity security or policy may seek to promote particular developments in specific industries.

The thesis consists of six papers, each of which is concerned with the application of multi-sectoral economic analysis and modelling. All six are published in peer-reviewed academic journals between 2007 and 2015 (inclusive). The applications range from specific energy technologies – i.e. an onshore windfarm development, biofuels and developments in marine renewable energy technology – to specific or potential energy policies – i.e. a (revenue-neutral) carbon tax and improvements in the efficiency of energy in production.

The sequence of papers presented in this thesis reflects a progression in the analytical complexity of the papers and applications. We begin with multi-sectoral economic accounts and "fixed-price" modelling techniques (IO and SAM), before moving to the more complex ("flex-price") CGE methods. We provide a brief overview of the key common and distinctive features of "fixed-" and "flex-price" models in Chapter 2.

This thesis explores the fundamental characteristics, assumptions and uses of "fixed" and "flex-"price models. Working sequentially from IO/SAM to CGE methods, it explores the particular strengths, weaknesses and usefulness of each of these modelling approach, and explains the contribution of the papers included in this PhD by published works to the academic literature and current policy issues in each area.

In the rest of this Chapter, we provide a very brief description of the features of each paper and then outline the structure of the thesis. More details on each paper is provided in Chapter 3.

The first paper utilises IO and SAM analyses to demonstrate the likely economic impact of establishing a large onshore windfarm on the Shetland Islands. The second paper explores the methodological applicability of "fixed-price" and "flex-price" techniques in the modelling of the economic impacts of biofuels. By comparing the features of IO/SAM and CGE techniques, this second paper is thus a "bridge" between the multi-sectoral economic modelling approaches.

The third and fourth papers are primarily concerned with understanding the economic consequences for a regional economy of expenditures related to energy developments: specifically, how the assumptions of “fixed-” and “flex-price” models affect the scale and timing of economic impacts in response to a set of demand shocks. Crucially, we argue that fixed-price models are unable to appropriately capture the notion of “time”. Using a CGE for Scotland in both papers we reveal how the results from a ”flex-price” analysis sheds light on the timing of economic impacts.

The fifth paper uses a CGE model of the UK to explore the consequences of improvements in the efficiency of industrial energy use. There is a growing academic literature on the consequences for energy use of improvements in energy efficiency, and “flex-price” models are particularly suited to understanding these impacts. This paper is the first CGE application to assess the possible scale of the “rebound” effect from improvements in energy efficiency for the UK. The sixth (and final) paper uses a CGE model of Scotland to assess the impacts of a tax on carbon emissions, assessing whether such a policy might bring about a “double-dividend” in the sense of simultaneously achieving both reduced emissions and increased economic activity.

1.1 The structure of the thesis

The thesis is structured as follows. Chapter 2 describes firstly the common features and then the distinctive features of the ‘fixed” and “flex-price” modelling approaches used in the papers contained in this thesis. Chapter 3 summarises the six papers included in this thesis, including bibliographic details (Section 3.1) and a description of the content and summary of the main contribution of each paper (Section 3.2). Chapters 4 to 8 contain the specific details of the contributions made by each paper to the academic and policy literature. Each Chapter begins by stating the challenge for policy, before covering the multi-sectoral methodology used in each Paper. The final section of each Chapter notes the specific contributions made by each paper to the academic and policy literatures. Chapters 4 to 8 are entitled:

- Chapter 4: The introduction of a new sector into "fixed-price" systems (Paper 1)
- Chapter 5: The modelling of new biofuels activities (Paper 2)
- Chapter 6: The impacts of expenditures on new energy capacity: model specification, "legacy effects" and local content (Papers 3 and 4)
- Chapter 7: CGE modelling of energy efficiency improvements (Paper 5)
- Chapter 8: CGE modelling of Environmental Tax Reform and the "double-dividend" (Paper 6)

Chapter 9 describes potential future research from each of the papers included in this thesis, while Chapter 10 provides conclusions.

2 Features of fixed- and flex-price approaches

2.1 Common features

All six of the papers in this thesis extend and apply multisectoral modelling approaches. In the brief description of each paper which follows in Chapter 3, we label the specific modelling approaches used as either “fixed-” or “flex-price”. These terms have specific meanings, which relate to the features of the approaches. This section describes the commonalities of both “fixed-” and “flex-price” approaches, before Sections 2.2 and 2.3 respectively briefly set out the distinctive features of each approach.

Both approaches share three common, useful features. First, they are explicitly multisectoral in nature, and so can permit industrial sector specific analysis, with total effects given as the sum of industry-specific impacts. There are standardised definitions of industrial sectors into which all economic activities are conventionally categorised. Thus, every economic unit – a factory, office or energy facility – can in principle be identified and matched to an economic sector. This feature makes these models particularly useful for examining the *ex ante* impacts of, for example, the introduction of new industrial activity, or expenditures which are distributed across sectors, or policies which have quite different impacts across sectors depending on their characteristics (e.g. the introduction of a carbon or energy tax, given the wide variation in energy use and emissions across sectors).

Second, both can be used to identify the consequences of sector-specific changes on the broader system as a whole. With regard to the economic impacts of changes in sectoral activities, both “fixed-” and “flex-price” systems use the interdependencies among parts of an economy to quantify the wider “knock-on” impacts that may result. While such approaches have necessary assumptions and characteristics, which are described briefly below and in more detail later, both provide a rigorous approach to analysis. In the absence of any methodological framework, the policy maker would be left without means to understand *ex ante* the possible implications of a policy. The qualitative and quantitative results from "fixed-" and "flex-price" models can inform the design of policy, or hypothetical policy options. Such results could include measures which aligned with the (multiple) objectives of energy policy, introduced in Chapter 1, as well as changes in other variables that are incorporated within the economic or energy-economy-environmental modelling framework.

Third, the results of both approaches will reveal disaggregated impacts, which could relate to specific industrial sectors or periods of time. Thus, the sectoral consequences of policy decisions could be identified and mitigation policies designed, as could the aggregate impacts of sector-specific shocks. Additionally, as sectors may have quite different energy or environmental effects, only by knowing the sectoral distribution of impacts will the aggregate impacts on these variables be quantifiable. Further, time period(s) over which results are felt could be critical. For instance, political economy considerations, including elections and the lifetime of elected governments, may lead to a focus on impacts in the short-term, and the neglect of longer term impacts.

2.2 Fixed price

Input-Output (IO) is the most widely used method of regional analysis (while it is also commonly used for modelling national economies) and is flexible and versatile enough to be applied to economic development, trade, environmental and energy questions (Rose and Miernyk, 1989). IO analysis typically takes one of two forms: first, as an accounting framework – revealing the nature of production and consumption links in a set of economic accounts – and second, for modelling the impact of specific changes in economic circumstances. In their first use, IO accounts can reveal the economic relationships ("linkages") between sector(s) of an economy and between production and consumption activities (Leontief, 1936, 1941; Rose and Miernyk, 1989; Miller and Blair, 2009)[2]. Social Accounting Matrix (SAM) analysis extends the coverage of IO accounts with more information on the flows of transfers and payments/receipts between sectors, institutions and factors of production within an economy (Stone, 1986). A SAM can be considered as an extended set of IO accounts as it portrays all income flows between institutions and agents in an economy, of which IO accounts are only part (e.g. Stone (1961, 1986)).

2.2.1 Economic accounts

A set of multi-sectoral economic accounts show the interrelationships among sectors of the economy. The pioneer of the Input-Output (IO) approach, Wassily Leontief, wrote in the first statement on IO accounts, (Leontief, 1936, p. 106), that his "scheme" is rather simple:

> "The economic activity of the whole country is visualised as if it were covered by one huge accounting system. Not only all branches of industry, agriculture and transportation, but also the individual budgets of all private persons, are supposed to be included within this system."

It provides a set of economic accounts therefore for a period of time, "say a year, a month or a week":

> "It registers on its credit side the outflow of goods and services from the enterprise or household (which corresponds to total receipts or sales) and on the debit side the acquisition of goods or services by the particular enterprise or households (i.e. corresponding to total outlays). In other words, such an account gives a description of the flow of commodities and services as it

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[2] There is a significant literature using such accounts as the basis for developing measures of the importance of individual ("key") sectors within that economy (for example, Hewings 1982; Cella 1984; Dietzenbacher 1992). This uses the linkages between sectors – explicitly identified in IO accounts – to understand the connections between different sectors within an economy. Such linkages can be used to identify those which have an above average impact on the rest of the economy, and are designated as "key" sectors for the economy.

> enters the given enterprise (or household) through one end and leaves it by the other."

Table 1 shows a schematic of an Input-Output table. The single-entry principle is evident as items on rows (receipts) are also on columns (expenditures). By construction therefore, the sum of the row and column relating to sector i will be equal, as each expenditure item is matched by a receipt. The matrix T_{11} will be square with dimensions NxN, where N is the number of sectors identified. This contains the explicit interindustry (and intraindustry for diagonal elements) exchanges of goods between sectors i and sector j, where i,j are the producing sector (which earns receipts for its output) and the purchasing sector (which makes expenditures) respectively. Sales to households by production sectors are given in the Nx1 vector T_{13}, while sales to other elements of final demand are identified in matrix F_1, which could typically include column vectors showing purchases of sectoral output by government, export demand and for investment. Matrix T_{21} shows the sectoral payments to factors of production (labour and capital), while purchases of imported goods are given in matrix X_1.

As noted earlier, the identified payments for factors in an IO table are solely those related to production in that period, i.e. wages paid for employment by sector j for the purposes of producing output *in the period to which the IO tables relate.*

Multisectoral economic accounts were developed further through the work of Richard Stone (Stone, 1961) on the Social Accounting Matrix (SAM). SAM accounts include "institutions" which are not necessarily featured in IO systems (e.g. Stone 1986; Relnert and Roland-Holst 1997) and so extend the basic IO accounts from its focus on the production and consumption aspects of economic accounts, with a more comprehensive coverage of flows of income among transactors (e.g. Pyatt and Round 1977, 1979; Pyatt 1988, 1999). A simple schematic for a SAM is shown in Table 2. A comparison between Tables 1 and 2 makes clear the additional information required for construction of a SAM for an economy, as matrices T_{32}, T_{33}, F_3 and X_2 – most commonly relating to financial transfers between institutions, factors and the external account – are not provided in IO accounts.

Table 1: Schematic layout of an Input-Output table

	Expenditures		
Receipts	Production activities	Final demands	Gross output
Production activities	T_{11}	T_{13}+F_1	Y_1
Factors (i.e. labour and capital)	T_{21}	F_2	Y_2
Imports	X_1	X_3+X_4	Y_X
Gross inputs	Y_1	(T_{13}+F_1+F_2+X_3+X_4)	–

Table 2: Schematic layout of a Social Accounting Matrix

	Expenditures				
Receipts	Production activities	Factors	Institutions (i.e. households and companies)	External account	Total receipts
Production activities	T_{11}	–	T_{13}	F_1	Y_1
Factors (i.e. labour and capital)	T_{21}	–	–	F_2	Y_2
Institutions (i.e. households, government, companies and capital)	–	T_{32}	T_{33}	F_3	Y_3
External account	X_1	X_2	X_3	X_4	Y_X
Total expenditures	Y_1	Y_2	Y_3	Y_4	–

2.2.2 Fixed-price modelling

When used for economic modelling, the most common configuration of IO and SAM systems is as demand-driven systems, in which all economic activity can be attributed to exogenous demand, and through which the consequences of changes in demand can be quantified[3]. The decision about those economic activities which are "exogenous" and those which are "endogenous" to economic activity is critical for the resulting economic consequences. Exogenous elements are assumed to be unaffected by the consequences of the change in economic circumstances, while endogenous elements are those which are affected. The consequential change in endogenous elements leads to further changes in other related endogenous elements, producing a "rippling" of economic impacts throughout an economy.

In both IO and SAM approaches, the interdependencies between sectors – as given in the set of accounts – form the basis for how changes in one part of the system (which could be a sector) have consequences elsewhere (i.e. in other sectors). For instance, under the conventional demand-driven perspective, economic activity is supported by exogenous final demand, and so changes in (exogenous) demand cause changes in (endogenous) variables, such as sectoral output, etc.

The "multiplier" refers to the notion that a disturbance (the "direct effect") may "ripple" through the economy, creating "knock-on" effects in endogenous accounts. In the simplest form, an initial (positive) change in demand for the output of a sector will subsequently increase the demand for the output of those sectors which provide inputs to the directly stimulated sector(s), which in turn generates additional demands for the output of other sectors through their sectoral interlinkages, provoking a multiplicative effect from the initial stimulus. This simple analysis refers to a situation where only

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[3] There have been supply-side models using IO, with an extensive literature dating from Ghosh (1958), in which changes in the supply of inputs can have knock-on consequences for total supply. The interpretation of such models have been questioned (Oosterhaven, 1988) with recent interpretations of the Ghosh model as a price, rather than quantity, model (Dietzenbacher, 1997).

production sectors are treated as endogenous to the economic system, and the associated multipliers are referred to as “Type I”. In an extension, the household “sector” can be endogenised, closing the loop between changes in demand and subsequent changes in the level of household (wage or total) income and expenditures, and the resultant multipliers are referred to as “Type II”. Closing the IO model in this way – “with respect to households” – generates a larger multiplier as induced changes in incomes stimulate further changes in consumption, and so additional “knock-on” effects.

SAM accounts can also be used for modelling the consequences of changes in economic structure or demand (Pyatt and Round, 1979; Pyatt, 1988; Roland-Holst, 1990; Blancas, 2006; Alejandro Cardenete and Sancho, 2006). Critically, SAM modelling allows for the “endogenising” of institutions and factors that are not captured in IO accounts as the latter relate solely to production and consumption activities within an economy. More detailed analysis of IO and SAM modelling, and the calculation of the simple demand-driven multipliers, is presented in Appendix A.

2.2.3 Assumptions of fixed-price modelling

When IO and SAM accounts are used for economic modelling purposes, they share a set of common assumptions (e.g. West (1995); Miller and Blair (2009)).

A critical assumption of IO and SAM modelling is that in their demand-driven specification, they assume no supply-side constraints, i.e. all sectors are able to find available resources to permit that expansion at prevailing prices. This would be equivalent to assuming that there is an infinitely elastic supply on inputs for all sectors. For these reasons, IO and SAM modelling methods have been referred to as “fixed-price” – e.g. Partridge and Rickman (1998); Koh et al. (1993) – a nomenclature we continue in this thesis. There are two implications of this assumption of perfectly-elastic factor supplies.

First, IO and SAM approaches assume that exogenous accounts are not affected by endogenous variables, so that "crowding-out" cannot occur. For instance, in undertaking analysis of the level of government spending, "fixed-price" models would typically assume that changes in the level of government spending would not lead to any impact on the level of export demand (as both are exogenous). Partridge and Rickman (2010, p.1312) acknowledge that IO models are "incapable of estimating the potential supply-induced displacement of other economic activity".

Second, "fixed-price" systems assume that there is therefore no scarcity in any market, so that changes in demand have no impact on the relative prices in the economy. With unchanged relative prices for inputs, no industry has an incentive to substitute between inputs. This therefore gives rise to fixed technical coefficients in production, where these are fixed at their values as given in the IO accounts for the base year dataset [4]. That is, the input requirements of endogenous sectors are characterised by constant returns to scale, with the marginal changes in inputs calculated from the average inputs to each sector as given in the initial accounts. For example, if the economic accounts describe sector j as purchasing 5% of its input requirements from sector i, whatever the scale of sector j it would continue to require this same share of its inputs from sector i. This implies that there is no substitutability between inputs in production, i.e. that there are right-angled isoquants for each sector's production function, implying that sectoral output cannot increase without equiproportional increases in all inputs.

2.3 Flex–price

The theoretical notion of general equilibrium dates to the work of Leon Walras (Walras, 1874). However, it was only with the work of Kenneth Arrow and Gerard Debreu (Arrow and Debreu, 1954) and subsequent advances in computer power that computationally tractable general equilibrium models could be solved (Scarf, 1969). Funda-

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[4] Miller and Blair (2009) also refer to these as input-output coefficient and direct input coefficient.

mentally, computable general equilibrium (CGE) systems characterise the economy by a set of equations relating to production and consumption. Equilibrium outputs are determined simultaneously through solving every market for a specific set of prices, i.e. through the equality of demand and supply. We refer to models with these properties as “flex-price” models as prices adjust to “clear” all markets, and to contrast these to the more restrictive (“fixed-price”) models introduced above.[5]

Such models were initially focused on issues at the national level. See for example Shoven and Whalley (1984) for a review of early CGE trade models. Recently however there has been increasing use of these models for regional analysis (Partridge and Rickman, 1998, 2010).

It should be noted that the precise nature of markets for a given theoretical or practical application of CGE modelling can be incorporated in the model’s assumptions. This is part of a broader point, that, while sharing such common features, the precise specification of CGE models will vary between applications as the focus of each model differs. Therefore it is less possible to describe the general features and specific assumptions of CGE models since these can vary substantially. The points which follow therefore describe the basic requirements for CGE models, but may not describe all such models.

Given the need to specify the nature of production, consumption and distribution structure within an economy, the construction of a CGE modelling system is particularly data and parameter dependent. Some of this information – such as the level of aggregation (or disaggregation) of the economy into industries, and the nature of initial equilibrium consumption and distribution elements – can come from a set of economic accounts for the region or nation being modelled (were these data to exist). Indeed, many CGE models use IO and SAM accounts to provide the initial equilibrium

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[5] Markets may not “clear” in the sense of matching aggregate demand and aggregate supply through, for instance, imperfect competition in the labour market, meaning that its equilibrium might be characterised by the presence of involuntary unemployment.

state of the economy in question (Partridge and Rickman, 2010). Additionally, the behavioural side of the model, how the economy adjusts and what characterises the nature of equilibrium will be constructed by the model "builder" at the model specification stage.

As we saw earlier, the conventional assumptions in "fixed-price" systems include that there are technical coefficients which are fixed, with constant returns to scale in production, and an entirely passive supply side. While these assumptions can be imposed or emulated in a CGE model, a broader range of possibilities can also be considered (McGregor et al., 1996). For instance, sectoral hierarchical production functions can permit substitution between inputs in response to changes in the relative prices of inputs. In this way, the IO/SAM framework can be considered as a "special case" of a CGE model with specific assumptions imposed.

A further important element of model design is the treatment of time, i.e. whether the model considers the "dynamic" consequences of disturbances, or is restricted to considering the comparison of "static" equilibria. This can be important for understanding the impact of disturbances which themselves have a time dimension, e.g. a series of temporary demand-side shocks, or where there is policy interest in the timing of economic impacts, such as if a policy target will be met within a defined period of time. As will be seen in Chapter 6, how time is characterised in CGE models – including how this differs to an IO framework – has important consequences for the scale and timing of economic impacts from temporary and permanent demand shocks.

Furthermore, as the supply and demand side of each commodity market in the economy are explicitly modelled, CGE models have a further advantage over "fixed-price" models. While "fixed-price" systems typically assume the economic system to be demand-driven, "flex-price" models can be used to analyse the consequences of supply-side disturbances directly. They can therefore explore the consequences of supply-side disturbances, such as improvements in energy efficiency in use, and changes in the supply of factors (such as available labour force) caused by increased migration to an economy. Many economic policies act initially on the supply side and would require to be (inappropriately) translated into a demand-side disturbance to be considered in conventional “fixed-price” modelling. The “flex-price” CGE modelling of supply-side policies, specifically, improvements in energy efficiency in industrial use and the introduction of a (revenue-neutral) carbon tax, are the focus of the final two papers in this thesis.

3 The papers in this PhD by published works

3.1 Bibliographic details of papers

As stated in Chapter 1, this thesis contains six papers, all published in peer-reviewed academic journals. The papers span the period 2007 to 2015, with four of the six papers published in 2014 or 2015. Paper two is sole-authored, while the other five papers are co-authored. As required for the fulfilment of this PhD by published works, a detailed statement about the contribution of the PhD candidate to the co-authored papers is provided in Appendix B.

The papers included are the following (with the number being used to identify each paper in the thesis which follows):

1. "The importance of revenue sharing for the local economic impacts of a renewable energy project: A Social Accounting Matrix approach", (2011), Regional Studies, Vol. 45(9), p. 1171–1186 (with P. McGregor and K. Swales);
2. "The regional economic impacts of biofuels: A review of multisectoral modelling techniques and evaluation of applications", (2015), Regional Studies, Vol. 49(4), p. 615–643;
3. "Regional employment impacts of marine energy in the Scottish economy: A general equilibrium approach", (2015), Regional Studies, Vol. 49(2), p. 337–355 (with M. Gilmartin);
4. "The economic impacts of marine energy developments: A case study from Scotland", (2014), Marine Policy, Vol. 43, p. 122–131 (with P. Lecca, P. McGregor and K. Swales);
5. "The impact of increased efficiency in the industrial use of energy: A computable general equilibrium analysis for the United Kingdom, (2007), Energy Economics,

Vol. 29, p. 779–798 (with N. Hanley, P. McGregor, K. Swales, and K. Turner)[6];

6. "The economic and environmental impact of a carbon tax for Scotland: a computable general equilibrium analysis" (2014), Ecological Economics, Vol. 100, p. 40–50. (with P. Lecca, P. McGregor and K. Swales).

Table 3 describes publication details of the papers included in this PhD by published works. The more recent papers, published in 2014 and 2015, have yet to attract significant numbers of citations but there is evidence of the earlier work becoming influential and making a contribution to the academic literature[7].

Table 3: Publication details of each paper

Paper no.	Reference	Journal	Date submitted (Date accepted)	Citations	ABS 2015 ranking
1	Allan et al. (2011)	Regional Studies	Nov 2008 (Mar 2010)	14	3
2	Allan (2015)	Regional Studies	Sep 2011 (Apr 2013)	3	3
3	Gilmartin and Allan (2015)	Regional Studies	Aug 2012 (Jan 2014)	1	3
4	Allan et al. (2014a)	Marine Policy	Dec 2012 (May 2013)	10	2
5	Allan et al. (2007c)	Energy Economics	Jul 2006 (Dec 2006)	97	3
6	Allan et al. (2014b)	Ecological Economics	Jun 2013 (Jan 2014)	8	3

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[6] This paper began as a report for the UK's Department for Environment, Food and Rural Affairs (DEFRA), published in May 2006 (Allan et al., 2006).

[7] Citations were obtained from Google Scholar on 30th August 2015.

Table 4: Research focus of each paper

Paper no.	Energy technology or policy	Empirical or review piece	If empirical, "fixed" or "flex-price" modelling	Scenario considered	For dynamic models, backward- (BL) or forward-looking (FL)?	Spatial focus
1	New Onshore windfarm	Empirical	Fixed (IO/SAM)	Onshore windfarm in IO and SAM	Static	Shetland Islands
2	New Biofuels production	Review	–	Introduction of new biofuels production in Fixed- and Flex-price models	–	Regional and national (plus intra-) models
3	Expenditures on Marine energy capacity	Empirical	Flex (CGE)	Temporary and sequential demand shock	BL	Scotland
4	Expenditures on Marine energy capacity	Empirical	Flex (CGE)	Temporary and sequential demand shock	BL and FL	Scotland
5	Improved energy efficiency in industrial use of energy	Empirical	Flex (CGE)	Permanent supply-side shock	Static	United Kingdom
6	A revenue-neutral tax on carbon	Empirical	Flex (CGE)	Permanent supply-side shock with revenue-recycling	BL and FL	Scotland

3.2 Summary of the content and contribution of each paper

This section provides a brief description of the multi-sectoral modelling techniques used in each paper that forms part of this thesis. As noted above, the sequence of papers reflects increasing complexity. Table 4 provides summary details of the specific content and contribution of each paper.

3.2.1 Paper One (Allan et al., 2011)

Paper One examines the use of "fixed-price" economic models to explore the consequences of the introduction of a new onshore windfarm with significant non-wage income links to the local economy.

The concept of a Type I and Type II "multiplier" was introduced briefly in Section 2.2. In the latter, wage income is endogenised, "closing the model" with respect to households, and linking wage income to household consumption. IO modelling however does not endogenise *non*-wage incomes. Such non-production incomes (such as pensions or returns to capital and profits) are identified in a Social Accounting Matrix (SAM) which was also briefly described in Section 2.2.

We described briefly earlier how SAM modelling permits the "endogenisation" of institutions and factors which are not themselves captured in IO accounts. When new projects have links to the rest of the economy through the purchasing of inputs, the provision of sales to other (local) sectors and through employment, and therefore wage payments, both IO and SAM models can capture the "knock-on" impacts of these new activities. However, for projects which have limited linkages to the rest of the economy and where they generate substantial non-wage income flows, for instance, ownership profits, these can only be appropriately considered in a SAM system.

Paper One demonstrates the added value for using SAM rather than IO modelling to understand the economic consequences of a new renewable project. The specifics of this proposed project – a large onshore wind farm on the Shetland Islands – are complex, and interesting: in particular there are potentially large non-wage income links between the project and the economy through the local community being involved in the project with a share in ownership.

We identify the contribution of Paper one by examining its relationship to the existing literature at the time of publication. While the paper identified some previous work which had used multi-sectoral models to explore the regional economic impacts of electricity generation (Tourkolias et al., 2009; Rose et al., 1982), and earlier work on the use of such models for examining the consequences of regional ownership of energy developments (Swenson and Eathington, 2006b,a) there had been no previous application of IO or SAM techniques to onshore wind developments.

Comparing the IO and SAM modelling results, Paper One demonstrates that a SAM approach is able to explore these non-wage income flows. It is also used to demonstrate the importance of these for the potential economic impacts both in aggregate and by industrial sector, on GVA and employment, of the project. Additionally, sensitivity analysis demonstrates the importance of the treatment of the retained income flows (specifically, how these additional incomes are respent within the local economy).

3.2.2 Paper Two (Allan, 2015)

The global production of biofuels – e.g. bioethanol and biodiesel, derived from agricultural crops specially grown for the purposes of being processed into transportation fuels – enjoyed a growth of 375% between 2001 and 2009. Much of this growth is the result of policies designed to reduce emissions by increasing biofuels' share in total transport fuels as well as for economic development reasons, such as increasing employment in the production of biofuels. Both "fixed-" and "flex-price" models have been used to explore the potential economic impacts of new biofuels production. This (sole-authored) paper describes "fixed-" and "flex-price" modelling methods before discussing the appropriateness of each for understanding the *ex ante* economic consequences of new biofuels production.

Paper Two identifies and critically reviews (nine) applications of IO/SAM modelling of biofuels (including, e.g. Swenson and Eathington 2006a,b; Low and Isserman 2009) and (six) CGE studies (including, e.g. Gehlhar et al. 2010; Arndt et al. 2010). The paper therefore reviews applications of these modelling approaches and contrasts the strengths and weaknesses of the approaches themselves for understanding the consequences of new biofuels production. In critiquing the usefulness of "fixed-" and "flex-price" approaches, Paper Two provides a "bridge" between the IO/SAM approaches of Paper One and the CGE applications of Papers Three to Six.

The paper demonstrates that, while each technique has particular strengths, the specific consequences of biofuels production are more appropriately captured using carefully specified CGE models, particularly where the treatment of usable land as a factor of production is properly, and therefore explicitly, considered. CGE methods appear to offer significant benefits relative to fixed- price methods by allowing for prices to respond endogenously and therefore land use (in aggregate and by sector) to respond to market signals, while also permitting alternative specifications for the supply conditions of the factor itself. Failing to implement the correct treatment of scarce factors of production —such as the availability of suitable land for growing biofuels crops —means that conventionally applied "fixed price" methods are unlikely to be appropriate[8].

It is critical therefore that the assumptions of IO/SAM modeling – briefly described in Section 2.2 – are taken into account when such models are used to examine the economic impact of new biofuels production. Paper Two therefore makes a contribution to multi-sectoral modelling "best practice" for the specific case of the modelling of biofuels

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[8] There are proposed modifications of the conventional IO/SAM modelling approach to take account of sectoral output constraints (e.g. Steinback (2004). The paper argues that: "The existence of supply constraints can be introduced withn demand-driven IO and SAM approaches. These work, however, by reallocating the demand for sectoral output, and therefore 'mimic' the outcome of resource constraints rather than systematically model the existence of those constraints" Allan (2015, p.6).

production: it is intended to be similar in sprit and usefulness to other comparative modelling papers in the multisectoral modelling literature (e.g. Koh et al. (1993); West (1995); Partridge and Rickman (1998, 2010)). The focus of Paper Two is however less general than these papers since it focuses on the usefulness of these techniques to the modelling of new biofuels activities.

3.2.3 Paper Three (Gilmartin and Allan, 2015) and Paper Four (Allan et al., 2014a)

It has been often argued that a natural consequence of developments of new renewable energy capacity is an economic advantage for the "host" region, as well as an environmental benefit from producing electricity from low emissions sources. The specific scale and timing of the economic impacts that could arise from renewable energy developments are not clearly understood in the academic and policy literatures, with the transmission mechanism between the development of the capacity and the economic impact either assumed or ignored.

Papers Three and Four explicitly explore one such transmission link, which is the expenditures associated with the development of new marine energy capacity and made in the local (Scottish) economy. Their broadly shared methodological approach means that both papers are considered jointly in this thesis. There are however differences in focus of each paper: Paper Three examines the impact of hypothetical marine developments in Scotland (of 500MW, 1,000MW and 2,000MW respectively by 2020), while Paper Four takes expenditure figures from projects (with a total capacity of 1,600MW) proposed for the Pentland Firth and Orkney Waters area – of the Northern Coast of Scotland – which had recently obtained planning approval from The Crown Estate.

The scale of expenditures considered in both gives these the characteristics of mega-projects, i.e. projects with expenditures which are large in relation to the scale of the host economy. "Fixed-price" approaches can be used to show the knock-on effect of temporary expenditures, as we discuss in Section 6.4.3. Wassily Leontief developed Dynamic IO systems (Leontief, 1970), which form the basis for this section and much of the theoretical work in this area to date (e.g. Steenge and Thissen 2005). Some recent applications of IO analysis to demand shocks which have a time dimension have employed the "rounds" of the multiplier (introduced in Appendix A) to distribute changes in activity over time periods. Such approaches can incorporate lags or anticipatory behaviour by sectors imposed on an *ad hoc* basic by the modeller, but suffer from making the same assumptions, for example, about the supply-side of the economy as discussed in Section 2.2.3.

Papers Three and Four employ a "flex-price" (CGE) model for Scotland to explore the system-wide consequences of a set (across components (and industrial sectors) and over a number of time periods) of expenditures related to new wave and tidal energy capacity. In each Paper the results from a CGE analysis are compared against those from IO models – as these models are commonly used to explore the consequences of demand-side shocks.

These are shown to have system-wide impacts through, for example, tightening the regional labour market by increasing the demand for labour. Unlike reports to date which use IO methods, the CGE models used in Papers Three and Four introduce supply-side (i.e. labour and capital) constraints on economic activity, which gives rise to crowding out and displacement in the short run. These constraints on factors of production can however ease over time through migration and investment respectively.

Both papers demonstrate aggregate impacts under CGE analysis which are much smaller than those from IO, particularly during the periods of the demand shocks. Further, the CGE model results exhibit what we have termed "legacy effects", i.e. impacts which occur beyond the end of, but as a direct consequence of, the demand side disturbances. These papers explore which model features are critical in determining the existence, size and duration of legacy effects. As we shall see, one factor which gives rise to legacy effects is the assumed behaviours of households and firms, for instance, whether they behave "as if" they are myopic (i.e. backward-looking) or take decisions on consumption and investment with a forward-looking perspective. A significant difference between Paper Three and Paper Four is that the latter employs a forward-looking model (as well as myopic perspective) while the former adopts a myopic perspective.

Fundamental, therefore, for the context of Papers Three and Four is an examination of the IO literature on the modelling of (demand) disturbances which have a time dimension. We also show how the analysis undertaken in these papers contributes to the corresponding CGE literature. Reviewing the recent regional CGE literature, (Partridge and Rickman, 2010, p.1315) argue that, "To become more widely adopted, regional CGE models need to predict the time path of economic responses to policy changes. Policymakers want to know when initial impacts are expected and the required period for full responses to be realised". We discuss the AMOS CGE model which is employed in both papers in Section 6.3, while in Section 6.4 we describe how this specification of the model compares to IO analysis and can thereby give rise to economic impacts of temporary demand-side expenditures which themselves have a time dimension.

3.2.4 Paper Five (Allan et al., 2007c)

Energy efficiency has gained a central place in environmental and energy policy. Despite this, the term "energy efficiency" is often misunderstood, and so are the plausible consequences of policies designed to improve the efficiency in energy use. The most typical interpretation of energy efficiency – applied to households and industries equivalently – might be along the lines of "making more with less energy", or perhaps "maintaining existing levels of output or energy services while using less energy". The implication of both statements is that improvements in energy efficiency lead to an unambiguous decline in energy demand.

However, since Jevons (1865) economists have appreciated that improvements in efficiency in resource (including energy) use will not necessarily lead to the same scale of reductions in physical resource use. Jevons' argued against the proposition that to reduce the use of coal (which many were fearing would run out) it was necessary to make the use of coal more efficient. He wrote (Jevons, 1865, p.141): "it is the very economy of its use which leads to its extensive consumption. It has been so in the past and it will be so in the future".

Jevons (1865, p.141-142) is clear on why this counter intuitive outcome would arise:

> "The number of tons used in any branch of industry is the product of the number of separate works, and the average number of tons consumed in each. Now, if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each."

Jevons is clear therefore that increasing the efficiency of a factor of production is unambiguously a source of economic growth. Much of the recent debate in the literature since the 1980's focuses on microeconomic and partial equilibrium analysis of the consequences of improvements in energy efficiency (beginning with Khazzoom (1980); Brookes (1990); Saunders (1992). This had centred on discussions about the potential existence of "rebound" – that is, reductions in energy use, but which are smaller than the proportionate improvement in energy efficiency – or (as Jevons (1865) identifies) "backfire", when improvements in energy efficiency actually lead to increases in the use of energy.

Paper Five is one of the first applications of CGE modelling to the system-wide analysis of improvements in the efficiency of energy use in industry. The advantages of using a CGE modelling system for examining the consequences of improvements in energy efficiency are several, although such models were not widely used until the early 2000s (Greening et al., 2000). First, as seen in Section 2.3, such models are grounded in economic theory, and require the modelling of the supply-side of the economy which is necessary for appropriate consideration of supply-side policies, such as improved efficiency in production. Additionally, such models can examine the "net" impacts of such policies, and so deal with the countervailing impacts within the economic system which could arise from a policy which is likely to produce countervailing effects of changes, e.g. lowering the requirement for energy to produce a given level of output, but also stimulating output through lowering the cost of an input to production.

The direct consequence of the improvement in energy efficiency is to lower the price of energy in efficiency units. While positive for economic growth, the impact on energy use therefore will depend on the price responsiveness of the general equilibrium demand for energy. This is an empirical question to which CGE modelling is uniquely able to contribute, particularly as such models can capture interactions between energy, economy and environmental systems. For example, in a "naive" energy system model where, in the most simple form, energy demands are exogenous while supply is provided through the optimisation (e.g. minimisation) of (system) costs, an improvement in energy efficiency would lower energy demand, with a necessary equivalent reduction in energy supply. An energy-economy-environment CGE model captures the interdependencies among each of the sub-systems and reveals the extent of any rebound or backfire.

The CGE application in Paper Five explores the consequences of improvements in energy efficiency in UK industries, and the existence and scale of the "rebound" effect following an across-the-board improvement in the efficiency of energy use in all sectors. The central results in the paper reveal that in the UK economy an efficiency improvement in the industrial use of efficiency across all sectors, leads to rebound in the short run of 55% and 30% in the long run. Additionally, extensive sensitivity analysis examined how long-run rebound is affected by key modelling assumptions and specific model parameter values, in particular, the elasticities of substitution in the production hierarchy and assumptions regarding wage setting in the labour market.

There is now a rapidly growing literature on the application of CGE approaches to understanding the empirical possibilities for rebound and backfire effects following improvements in energy efficiency, which includes other papers using the same (AMOS) general model framework, albeit for a different geography (Scotland rather than the UK, which is the focus of Paper Five) while more recent papers have more complex treatments of the energy system (Hanley et al., 2006, 2009; Turner, 2009; Turner and Hanley, 2011) and have examined improvements in energy efficiency by households (Lecca et al., 2014). In Section 7 we discuss the specification of the AMOS model in Paper Five and its contribution to the CGE modelling literature on the economic and energy consequences of improvements in energy efficiency.

3.2.5 Paper Six (Allan et al., 2014b)

As we identified earlier, one of the objectives of energy policy is reductions in the impact of economic activity on emissions, specifically carbon emissions. This is motivated by evidence linking anthropogenic activity to changes in emissions, causing changes in the global climate. At the most basic level, global emissions are an "externality" (Pigou, 1920), meaning that the production of emissions is not taken into account by households or firms in their production or consumption decisions, and leading to an overproduction of emissions.

While other methods might be used - such as the allocation of property rights - one energy policy instrument that could be useful in reducing emissions, is a carbon tax. Such an instrument would cause the use of carbon to be internalised in firm's production decisions, and could equate marginal private and social valuations (Pigou, 1920). Global carbon pricing has been proposed as a way to address the problem of ever rising carbon emissions and prevent the catastrophic global consequences of unaddressed climate change.

Bosquet (2000) examines the evidence for revenue-neutral environmental tax reform (ETR) – that is, shifting the burden of taxation from factors of production, i.e. labour and capital, to environmental 'bads' such as pollution, which are socially undesirable. He notes that the intention of ETR is to create "the potential for a 'double dividend', i.e. an environmental improvement [the first (environmental) dividend] coupled with an economic benefit [the second (economic) dividend]" and that the "double dividend hypothesis has been the cause of intense academic and political controversy in recent years" (Bosquet, 2000, p.20). The lessons from the earlier literature on this ex ante modelling of ETR will be reviewed when we consider the contribution of Paper Six.

Several features of CGE models make them particularly useful for exploring the consequences of a carbon tax. First, their explicitly multi-sectoral nature allows the identification of distributional winners and losers from ETR. Second, their system-wide focus captures the consequences of the introduction of a disturbance to a particular sector(s), factor or variable (such as emissions). A carbon tax would have the immediate consequence of increasing industrial input prices. While this would typically affect those industries which are heavy carbon polluters the most, all industries would see an increase in their costs and prices from this effect alone. This would likely damage the competitiveness of their output, and the Scottish economy as a whole, lowering economic activity. Unmitigated, these would lead to negative consequences for other aspects of the supply-side of the economy, such as investment and migration. Explicitly capturing the interactions between markets within an economy is a major strength of CGE ("flex-price") modelling, as seen in Section 2.3. Third, the overall economic impact of the policy – and the existence of a second (economic) dividend – depends upon the way in which revenue-neutrality is ensured, and alternative recycling routes have been explored in a number of CGE applications. The increased public revenue could be returned through reductions in the tax on labour, for example, which would benefit labour-intensive sectors, or as lump-sum transfers to specific groups. The evidence suggests that the specific way in which revenues from a carbon tax are returned to the economy are important for the scale of the second (economic) dividend from ETR (Patuelli et al., 2005) and so help in the design of energy policies intended to meet the multiple goals described in Chapter 1.

Paper Six uses a detailed energy-economy-environmental CGE model of Scotland to explore the environmental and economic implications of introducing a (hypothetical) revenue-neutral carbon tax on Scottish industries[9]. The Scottish Government has set ambitious carbon budgets and carbon dioxide reduction targets (i.e. a 42% reduction in CO2 emissions between 1990 and 2020, increasing to an 80% reduction in CO2 emissions by 2050 (relative to the 1990 level)) while at the same time there are pressures to further extend the range of tax powers under the control of the (devolved) Scottish Parliament. From April 2016, under the Scotland Act 2012, marginal income tax rates for Scottish taxpayers will be set by the Scottish Parliament, for example.

The paper shows that there can be positive economic consequences from the recycling (retention) of these additional revenues back into the Scottish economy. Critically, the way in which the increased revenues are recycled can offset the negative competitiveness impacts, resulting in simultaneous reductions in emissions (the “first dividend” and (under certain circumstances) increases in economic activity (the second “dividend”). Specifically, in the case where taxation revenues are recycled through a reduction in the rate of tax on labour income —reducing the unit labour cost to industries, while

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[9] A Scottish-specific carbon tax is, however not currently proposed. However the Scottish Government does have ambitious emissions targets and constitutional change, for example, to establish full fiscal autonomy could make such a policy feasible.

preserving workers take-home pay —we find a “double-dividend” of increased economic activity and employment and reduced emissions. In Section 8 we discuss the literature on the modelling of ETR using CGE models and the contribution of Paper Six to this field.

3.3 Brief recap on the academic literatures to which the Papers contribute

In this short section, we recap the academic literatures to which each of the papers included in this thesis contribute.

Section 4 examines one of the major uses of multisectoral models: the introduction of new sectors (in principle), before then considering how Paper One introduces the new operational windfarm sector into the SAM for the Shetland Islands (Section 4.3), including the treatment of ownership profits under alternative scenarios for local ownership, and the sensitivity of the results to the degree of local sourcing. The contribution to the academic and policy literature of these findings are then described.

Outlined briefly above, the assumptions of “fixed-price” modelling techniques of IO and SAM have important consequences for their appropriateness. One specific example of this, and the focus of Paper Two, is the relative strengths of “fixed-” and “flex” price models for considering the *ex ante* modelling of new biofuels production. We examine empirical applications of fixed-price approaches to new biofuels production in Section 5.3.1 and argue that appropriately constructed “flex-price” models are more appropriate for considering the consequences of these developments, in part due to their explicit accommodation – within the model – of the supply of land.

Papers Three and Four are primarily concerned with the use of multisectoral models to estimate the direction and timing of the consequences of demand-shocks which themselves have a time dimension. As such, and after setting out the scale of expenditures related to energy developments, our review of the pertinent modelling begins with an introduction to the CGE model which is used in Papers Three and Four, highlighting general characteristics, such as the treatment of production, consumption and trade. Section 6.4.1 discusses how this model considers the timing of economic impacts from demand-side disturbances, and the causes of observed "legacy" effects, which is the major methodological contribution of Papers Three and Four. The contrast between this and the use of the "rounds" of the IO multiplier to decompose multiplier impacts across conceptual time periods is discussed in Section 6.4.4. Section 6.5 describes how the approaches of Papers Three and Four suggest a direction to considering the impact of changes to the "local content" in energy developments – a major issue for current energy policy.

Papers Five and Six explore supply-side disturbances in a flex-price (CGE) environment, respectively addressing the effects of improvements in industrial energy efficiency in the UK – i.e. improvements in the efficiency by which energy is used in industrial production – and of a revenue-neutral tax on the emissions of carbon in the Scottish economy. Chapter 7 explores the use of CGE approaches to examining the scale of rebound and backfire effects from improvements in energy efficiency. Chapter 8 reviews the contribution that Paper Six makes to the literature on the existence and scale of the double-dividend from a revenue-neutral carbon tax.

Taken together, the six papers reveal how IO/SAM and CGE multi-sectoral economic modelling approaches can usefully explore the *ex ante* consequences on energy, economic and environmental measures of energy technologies and policies.

4 The introduction of a new sector into "fixed-price" systems

In Section 2.2, we indicated how multiplier techniques can be used to identify key sectors in an economy as well as the consequences for aggregate and sectoral economic activity of changes in demand. This section describes how "fixed-price" analysis might be applied to consider the impact of the addition of a new sector to an economy. This is the specific application in Paper One, which is concerned with the introduction of a new onshore windfarm on the Shetland Islands. Chapter 4 has four parts. First (Section 4.1), we describe the principal ways in which a new onshore windfarm could impact on local economic activity, including through local ownership of the facility. Second, in Section 4.2 we describe the addition of a new sector to an existing set of economic accounts. Third, we discuss the practical challenges of introducing the specific example of an onshore windfarm into a SAM for the Shetland Islands (Section 4.3), while Section 4.4 describes the academic and policy contributions of Paper One.

4.1 Links between onshore windfarms and the local economy

There are a number of ways through which an onshore farm is connected to the local economy in which it is located. Here we identify three key links between an onshore windfarm and the local economy. For this section, since the electricity from grid-connected onshore windfarms is not used locally, we do not consider the local use of the electricity (although, as we shall see, in Paper Two, in the case of biofuels one of the key features of biofuel production is that it can be used locally). In cases where there is local use of electricity, the analysis would be more complex[10]. The three demand-

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[10] For example, where electricity production and consumption takes place locally rather than relying upon supply from a (national) grid, the economic and environmental effects on the local economy will be affected by the choice of generation technology in place at the local level and the (average) emissions intensity of grid-electricity (and the consequences for the production of electricity, see Allan et al. (2015b). The environmental gain or loss for the national economy as a whole from this change is also unclear.

side "mechanisms" linking onshore wind developments and local economic impacts are:

- Local purchases during the pre-operational phase
- Local purchases during the operational phase
- The scale of income retained locally – ranging from local equity ownership and co-ownership, to "community benefit" arrangements

Taking these in turn, we begin with perhaps the most obvious connection – that some portion of the expenditures on the development, construction and installation of the windfarm could be made locally, and that this would create demand in the local economy, potentially generating impacts on local, regional and national economies through the multiplier effect. We will return to the issue of the importance of local content (specifically with regard to pre-operational expenditures) when we discuss Papers Three and Four (Section 6.5).

For now we note that the scale of total expenditures which will be made locally (i.e. in the vicinity of the renewable energy project) will be relatively small[11]. Only a small portion of total expenditure is likely to be made in the region in which the development occurs for a number of reasons, including the lack of sufficient scale for component production within the local economy. For example, the fabrication of major components is likely to make sense only at "scale", i.e. in a small number of major sites which would serve a larger market[12]. As well as being limited in their scale, expenditures at the pre-operational stage are also only temporary in nature. (The appropriate method to model the economic consequences of regional temporary expenditures linked to renewable energy developments is central to the discussion of Papers Three and Four in

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[11] Okkonen and Lehtonen (2016) report that 14% of the costs of the "Planning and construction" stage for community windfarms are likely to be made in the local economy.

[12] For example, a new facility in Hull – jointly supported by Siemens and Associated British Ports – will manufacture, assemble and service offshore wind turbine blades which are anticipated for the offshore wind projects on the East coast of England. It was reported that the first order for this facility was for a windfarm off the coast of Norfolk (BBC News, 2015a).

Chapter 6).

Second, there may be some amount of local economic activity supported by the operation and maintenance requirements of the site. Unlike the construction phase, such expenditures are not transitory, but persist for the project lifetime. Complex technological projects are likely to require a programme of regular maintenance and restoration. It is however not clear that onshore windfarms require such regular attendance and maintenance, apart from in extreme cases of turbine damage or technical faults. Additionally, the need for a regular workforce dedicated to one particular windfarm is small, with maintenance controlled and managed remotely in many cases. There is likely to be a greater share of the expenditures made within the local economy, compared to the construction phase. Okkonen and Lehtonen (2016) for instance, estimate that 63% of "Production" costs will be spent locally.

Finally, and most importantly for the analysis of Paper One, there could be regular financial flows between the windfarm and the local economy. Since the development of onshore wind in particular, communities near to renewable energy developments have been arguing for, in many cases successfully, financial transfers (see, for instance, Munday et al. (2011)). Such transfers could be a fixed annual amount (which may or may not be related to the operational capacity of the windfarm) although others have seen transfers linked to the electrical output of the facility in the preceding year. Such transfers in many cases occur over a defined period. These payments are intended as compensation for disruption to the local area and are always agreed after planning permission (as the provision of such transfers cannot be linked to the granting of planning permission). These are typically referred to as "Community Benefits", and could provide local community organisations with an income stream of some tens of thousands of pounds (or more, depending on the project size and the agreed lifetime). An additional route to local economic impact arises through the expenditure of this income.

There are, however, more recent examples of other forms of transfers between renewable energy projects and local communities. In Paper One, we specifically examine the case of the Viking Windfarm project on Shetland, which is co-owned by the Shetland Charitable Trust (SCT) (representing the community of Shetland Islands) and the utility company Scottish and Southern Energy (SSE). As a co-owner, the SCT would stand to gain a share of all revenues from the project, rather than receive a community benefit stream (which is likely to be a fraction of the size of any income stream from co-ownership). We explore this case in the following section.

Other forms of ownership structure are however possible, such as a (full) community-ownership model or an equity- (or debt-) funded community model – where the "community" may be local investors or a more geographically dispersed "community of interest", for example. Each ownership structure is likely to have different consequences for the amounts of income which may be retained locally, and therefore for the potential economic impacts at the local level from the operation of the onshore windfarm. In principle, different ownership structures could be examined using the methodology employed in Paper One.

4.2 The "final demand" and "inclusion" approaches

A major use of IO accounts and models is the assessment of the economic consequences of a new sector in an economy. Miller and Blair (2009) identify two possible ways of including new economic activity, which they refer to as the "Final Demand" and "Inclusion" approach respectively.

In the first (and using notation consistent with Appendix A), the analyst would have an L matrix for the economy under consideration and the new level economic activity would be found by identifying the direct spending of the new sector from existing sectors, and estimating a new (higher) vector of final demand (F^*). The new annual equilibrium level of output X^* would simply be:

$$X^{*} = LF^{*} \qquad (2)$$

The impact of the new industry would therefore be X^{*} minus X where X is the initial level of output (given as $X{=}LF$).

The “Inclusion” approach differs from the “Final demand” approach by identifying the changed nature of production, specifically that the new sector could sell part of its output to existing sectors in the economy. In this way, therefore, the analyst would require not simply the purchases by the new sector from the established sectors, but also its sales to the established sectors (and from itself). There would thus be a new A matrix and therefore new L matrices (A^{*} and L^{*} respectively) as the technical coefficients change. Miller and Blair (2009) show that we can specify the new level of equilibrium output as:

$$X^{**} = L^{**}F^{**} \qquad (2)$$

where L^{**} and F^{**} is the extended Leontief inverse and final demand vector respectively, i.e. where N sectors are in the initial IO or SAM accounts, these will have the dimensions $(N+1)$ x $(N+1)$ and $(N+1)$ x 1, respectively. The specific impact of the new industry/activity would be found by calculating X^{**} minus X.

For a new sector with purchases from, but no sales to, other sectors in the economy there would be no output being sold to sectors within the economy and so the technical coefficients remain unchanged as a result of the new sector. We can thus use the “Final demand” approach to capture the additional demand for the outputs of established sectors. Additionally, using a SAM rather than IO system, we can identify additional payments to each endogenous account (i.e. F_1^{*}) and model the consequences of these for economic activity. In the application in Paper One, the unique features of a windfarm with significant local co-ownership results in sizeable non-production income transfers which would not be captured within an IO system. We elaborate on these three points in Section 4.3.

4.3 New windfarm in Shetland IO and SAM

The approach in Paper One (Allan et al., 2011) is to identify a new row and column of the SAM for the Shetland Islands representing the backward and forward linkages of an onshore windfarm and a new final demand element representing the export of the output of this sector (the exported electricity in this case). The paper assumes that none of the electricity produced by the windfarm is used within the Western Isles economy, and so the structure (i.e. technical production coefficients) of existing sectors remain unchanged[13]. Using the extended SAM framework however requires the specification of the new sector – i.e. the purchases by the windfarm in a column and the (export) sales in a row – and an additional column and row showing the distribution of (ownership) profit income from the windfarm project.

The paper looks at two scenarios in the SAM framework:

- Scenario A assumes that there are only retained incomes comparable in scale to those which would accrue to the local (i.e. Shetland) community if standard Community Benefit-scale payments were made (these were assumed to be equivalent to £3000 per MW per year);
- Scenario B assumes a significant share of ownership profits are retained in the local economy. Importantly for the scale of the economic impact, it is assumed that all additional ownership income is respent in the same (fixed) proportions as

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[13] If the electricity generated by the facility is to be used locally rather than exported to the grid, this would change the calculations. For instance, the proposed Viking Windfarm would produce enough electricity for 335,000 homes (Viking Energy, 2015), while there are just over 9,000 households in Shetland, so in absence of a link to the GB grid the project would not be viable. The paper's focus is on the alternative ways in which the income flows from a grid-connected onshore farm could affect the local economy, so this assumption is appropriate.

existing local government spending. This is a reasonable simplifying assumption given that the community is a major investor in the project – through the Shetland Charitable Trust – which spends a significant amount on local infrastructure and charitable projects annually.

Across all scenarios and methods, the project has the same operational revenue from the sale of electricity to the UK electricity grid. The operational expenditures are also standard between scenarios – with relatively low local direct employment meaning £2.2 million of wages are paid each year by the windfarm, local and national taxes, imports (including of wind turbine parts) and charges for the use of the transmission network. Annual profits are the same in each scenario (£70.5million). However, as mentioned above, the use of these profits is radically different in the two scenarios, and consequently, is the economic impact of each scenario.

The paper begins by demonstrating the impacts of such projects if these were quantified using an IO system (with households' expenditures either being treated as exogenous – Type I – or endogenous – Type II). The Type I impacts are found by multiplying the new (extended) vector of final demand by the (extended) Leontief inverse in which the purchases and sales of the new windfarm sector are identified. Recall that it is assumed that the output of the windfarm is sold exclusively to exports, and the windfarm is assumed to make zero operational purchases from the local economy, so that the extended row and column entries (in the inter-industry element of the A matrix) are zero. This produces Type I economic impacts which are thus identical to the direct impact of the sector itself. There are zero stimulated interindustry activities in this scenario as the new sector neither displaces nor expands existing (Shetland) economy activity.

The Type II impacts require the use of the extended (Type II) inverse and vector of final demands. For the new windfarm sector, we specify the level of labour income, which increases household income and (because it is now endogenous) household consumption.

The aggregate impact of the new windfarm using the Type II framework on GDP is an additional £0.8 million of activity and a (GDP) multiplier of 1.01, while employment increases by 22 jobs for a multiplier of 1.43 on the directly created jobs in the windfarm itself. The percentage change in employment is larger than the GDP effect, reflecting both the low employment intensity of the windfarm itself and the high employment intensity of sectors in which Shetland household spending occurs.

In the two SAM scenarios, we endogenise factor income flows among institutions, and can show the importance of these for the scale of the economic impact. Such factor incomes are omitted from the IO analysis, which only focuses on expenditures and wage incomes. Specifically, as the windfarm project has no direct purchasing links to the local economy[14], Type I IO analysis is an inappropriate technique for demonstrating the impact that such a project could have on an economy, given that in both scenarios significant income flows would be retained locally.

In Scenario A, £3.3 million of profits from the windfarm remain within the local economy – these are allocated as £1.7 million to the Shetland Charitable Trust, £1.4 million to Shetland Islands Council (from increased taxation receipts) and £0.2 million in land rental payments to Shetland households – and are assumed to be distributed back to the local government and the household sector as appropriate. It is then assumed that these profit incomes contribute to additional local government and household income and expenditure. The distribution of such expenditures across sectors is assumed to be the same as for each account in the initial SAM for Shetland.

In Scenario B, locally retained profits increase to a total of £16.9 million – £1.4 million to Shetland Islands Council and £0.2million to households from land rentals, plus a total of £15.3 million from SCT's share of ownership incomes (net of debt interest payments). There is thus a more than four-fold increase in the amount of income retained in the local economy under Scenario B than Scenario A. The economic impacts

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[14] i.e. there is no local supply chain for intermediate inputs for the new windfarm sector itself.

of these scenarios increase GDP multipliers from 1.09 (A) to 1.31 (B) and job multipliers from 5.0 (A) to 15.39 (B) respectively.

4.4 The contributions of Paper One to academic and policy literatures

4.4.1 Ownership revenue retention can have a significant impact on the local economic impact

As the paper notes, the paper closest in spirit to Paper One is Swenson and Eathington (2006b). Their paper examines the cost structure for a facility to dry mill corn to produce ethanol in Iowa and introduce such a facility into a set of IO accounts, and sets out two cases of local ownership and the use of locally retained ownership incomes. Their purpose is to model the economic impact on the three-county region of this new production activity. The analysis begins with the creation of IMPLAN accounts for this economic region.

An important part of Swenson and Eathington (2006b)'s analysis is to adjust the IMPLAN economic accounts for this production facility. Unlike the onshore windfarm in Paper One, Swenson and Eathington (2006b)'s ethanol facility sells output locally and so changes the purchasing patterns of other firms within the regional economy. Similar to Paper One, Swenson and Eathington (2006b) also extends the IO analysis to a SAM of the local tri-country region to examine additional retained incomes and the assumed use of these in inducing additional economic activity.

That paper sets up two alternative cases of local ownership to retain ownership profits in the regional economy, which would have been treated as leakages from the region in an IO analysis. The categories of local ownership are termed “active investor” and “passive investor” respectively, and represent alternative consumption patterns by hypothetical investors in the ethanol facility. The former category – “passive investor”

– is assumed to treat the ownership profits received as additional income and respend in the pattern of local consumption, while the “active investor” is assumed to reinvest any additional income. In Swenson and Eathington (2006b)’s analysis in the base year SAM, this second category drives a lower amount of local spending for the same change in income: “active receipts are likely to be reinvested, like other investment incomes, with comparatively smaller portions converted to household consumption, according to the model mathematics. We are letting the underlying model structure determine the likelihood that these different dimensions find their way into regional spending” (Swenson and Eathington (2006b, p. 23)).

By considering alternative degrees both of local ownership (between 0% and 100%) and different divisions of that local ownership between alternative “investor” categories, Swenson and Eathington (2006b) estimate the consequences of these two ratios for the regional impact of the biofuels facility. They find that in the case of 50% local ownership, the impact of the plant on regional output can vary by \$1.8 million, with the higher impact when all investors are of the “passive” type (and when additional income is respent as household consumption, since in this case there is a higher marginal propensity to spend on local goods and services). For a given share of passive and active investors, however, an even larger change in economic impact can result from increased local ownership in total. For the case when passive and active investors are split 50:50 (which Swenson and Eathington (2006b, p.24) notes as being “a reasonable assumption for our plant”) the impact can vary by \$2.0 million for an additional 25% of local ownership in the facilty.

Unlike Swenson and Eathington (2006b), Paper One explores the impacts from alternative “local sourcing” of intermediate inputs. While in both Scenarios, by construction, zero intermediate inputs are sourced within the Shetland economy, there are plausible outcomes when there will be positive amounts of intermediate inputs “locally” sourced, which could be another route to additional economic impacts. The paper observes that, “it has been noted that if the 600MW project were undertaken on Shetland the Council would explore the economic viability of using local manufacturing facilities for elements of construction.” (Allan et al., 2011, p.11), and that a similar argument could apply to the operational phase of the project.

By varying the amount of local content of intermediate inputs, we assume a corresponding reduction in imports of inputs to the operational windfarm (with all other elements remaining unchanged, although in the sensitivity analysis in the paper we do jointly vary the level of local ownership and local sourcing of intermediate inputs). These calculations demonstrate that relatively large changes in the amount of intermediate inputs sourced within the Shetland economy produce relatively modest aggregate impacts, certainly compared to the impact of co-ownership. An additional 10% of inputs sourced locally increases local economic output by £2.2 million. The modest impacts reflect intermediate inputs being a small portion of total inputs. Jointly varying the level of local ownership and local sourcing highlights the importance of the existence and treatment of additional ownership incomes in the quantitative economic impact produced by an onshore windfarm.

Further, although the approaches differ, Paper One sits alongside a number of important recent academic papers examining the possible economic contributions of local and community involvement in the production of renewable energy (e.g. Munday et al. (2011); Phimister and Roberts (2012); Okkonen and Lehtonen (2016)).

Munday et al. (2011) do not undertake modelling activity, but do however provide a range of quantitative evidence about the financial linkages between an operational windfarm and a local area. They note that there has been “limited empirical investigation into the economic consequences of wind power in rural locations” (Munday et al., 2011, p.1) despite such projects often being located in areas which suffer with low economic activity and rurality. They are principally concerned with the links between projects and the “community”, which might either be that which is geographically proximate, or a community "of interest". They note a range of financial links between facilities and communities, which includes "community benefits" as outlined earlier in this Chapter. Other categories include "conventional economic benefits", such as local content in construction and operation, sponsorship of community events, payments of local taxes, or rents to local groups.

Munday et al. (2011) goes on to provide quantitative evidence on the existing links between wind energy projects and such communities. Several important points are found: the extent to which construction benefits local communities is affected by "a limited local supply side", with imports to the region common, particularly for turbines, including their servicing (which are provided by the manufacturers, and so not sourced locally). Civil engineering activities might be sourced locally, however in conclusion they report "the potential for leveraging economic benefits from wind generation for rural areas in the more conventional terms of investment, employment and taxation is fairly limited". Such evidence will be useful in Chapter 6 when we consider the extent to which expenditures on new energy capacity are made in a region.

More relevant for Paper One, Munday et al. (2011) finds that community benefit funds are in place for 21 of the 29 developments reviewed. Projects beginning after 1999 were more likely to have community benefits schemes, and also the funding for the community was larger in more recent projects (i.e. the payments per MW installed capacity were greater). Interestingly, Munday et al. (2011) finds that these funds were likely to be used for education and training[15], as well as energy projects, such as investments in energy efficiency, such as low energy lightbulbs, or environmental enhancement. Also importantly for future research, Munday et al. (2011) notes that community projects have little scope to use funds flexibly or outside of a narrowly defined geography, and that "there is very little evidence of the evaluation of funds and their economic outcomes" (Munday et al., 2011, p.8).

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[15] It would be expected that spending in such ways could lead to supply-side consequences, a point we return to in Section 9.2.

Phimister and Roberts (2012) use a regional CGE model of North East Scotland to show how the ownership structure of onshore wind farms, in particular their local income retention and the way in which that additional income is spent, could lead to differences in the economic impact of those technologies. In their application, they have three hypothetical ownership structures - “external” (in which the added wind sector is “100% owned by actors outside the North East Economy” (Phimister and Roberts, 2012, p.344)),“farmer” (where local farm households receive incomes from the wind sector) and “community” (where these incomes accrue to local “non-profit institutions” (NPIs)). In each of these two latter cases, two alternatives are modelled relating to the uses of the additional incomes retained: the consequences of which are detailed below.

Important similarities between Paper One and the work of Phimister and Roberts (2012) are that both consider an operational wind energy development in a small open regional economy and consider alternative levels of income retained within the regional economy. Construction expenditures are mentioned in Phimister and Roberts (2012) however are omitted from the analysis as these are both temporary and, given low local content, not likely to be important for local economic activity. Phimister and Roberts (2012) also acknowledge that a SAM framework is superior to IO for considering such impacts as factor income will be a very important connection between wind energy and the small regional economy (they further assume there to be very limited intermediate connections between the operational windfarm and the regional economy).

There are two significant differences between Paper One and Phimister and Roberts (2012). First, with regards to the retention of incomes, Paper One considers only changes in the level of incomes retained locally, and does not consider alternative possible uses of these incomes. In Phimister and Roberts (2012) the retained incomes are spent in alternative ways – either respent as consumption (by farm households or the NPIs respectively) or to increase the stock of capital (either in agriculture or the rural public sector)[16]. Secondly, as it uses a CGE framework, the Phimister and Roberts (2012) approach does not adopt the fixed-price modelling assumptions of linearity, fixed coefficients in production or the non-existence of crowding out. Usefully, however, for comparison to the results of Paper One, some key results are reported using the SAM approach. This permits us to directly see the additional impact of local income retention in the North East Economy.

The results of Phimister and Roberts (2012) concur with that of Paper one: specifically that additional local revenues have the potential to stimulate the local economy. They also report larger impacts in the SAM approaches, which is consistent with the fixed-price nature of the model. If we focus on the SAM results in each case, under "external" ownership case, GDP is increased by £69.3 million in the SAM case, compared to £79.05m and £92.25m in the farm households and NPI cases respectively. Comparing the external case with either of the two non-external cases it is reported that (Phimister and Roberts, 2012, p.348):

> "as expected, the level and distribution of household income [and GDP] changes substantially... due to the income from owning wind energy developments"

Additionally, the impact is greater when incomes are spent by NPIs as their spending is heavily focused in labour intensive sectors and so gives rise to a high induced multiplier effect which is not constrained in the SAM results reported. The consequences of additional capital stock is only reported for the CGE case – principally as introducing new capital stock would only have (temporary) demand-side consequences in a SAM models. The CGE results for these report more positive overall GDP and income effects than in the (CGE) cases where consumption is increased. Their results therefore "support the argument that community ownership of wind farm developments provides the greatest scope for retaining the income generated for the community" (Phimister

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[16] Phimister and Roberts (2012) note that as investment demand and capital are exogenous in their model, that results should be considered as occuring over the medium-term.

and Roberts, 2012).

Okkonen and Lehtonen (2016) examines the impact of wind power projects in Scotland, using IO multipliers. Unlike both Allan et al. (2011) and Phimister and Roberts (2012), they model the impact of construction expenditures, entering these as a demand shock. In three (hypothetical) scenarios, the assumed income to the community from the wind project is modelled as an increase to final demand for the output of local industries in alternative ways. Each scenario is argued to be consistent with local community development plans intentions for the use of such funds[17].

Okkonen and Lehtonen (2016) find that the largest annual impacts come during the construction phase, but also note that this is temporary in nature. The results for the different uses of the retained incomes and how these are respent reveal that the largest impact on incomes and employment to the regional economy come in the "Social services" scenario, when these are respent on Education and Health activities. As it is being modelled as a demand shock, this is likely to reflect the differential multipliers for each sector in the initial table, and so omits, for instance, the supply-side changes that the use of these expenditures could have[18].

4.4.2 Modelling can shed light on policy aspirations towards increased "community" role in energy production

There is increasingly a focus on the economic aspects of energy developments, including renewables, as part of the goals of energy policy. The example in Paper One – while quite an unusual example where the community becomes a significant co-owner of a major onshore windfarm project – demonstrates how important ownership incomes can be for the regional economic impact of that development. It also demonstrates that

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[17] For instance, in the "Social services" scenario, spending is allocated equally across Health, Education and Residential care services sectors, while in the "Infrastructure and communications" scenario, that same total expenditure is split equally across industries in the IO table relating to building and construction activities.

[18] For instance, Scenario C "Infrastructure and communications" would be likely to produce changes to the supply-side of the regional economy which are not taken into account in this paper.

such impacts would not be identified, let alone accurately measured, by a conventional IO analysis.

In Scotland, there is a growing focus on local and "community" energy developments. The recent target of the Scottish government calls for 500MW of capacity of "community-owned" energy by 2020 (Scottish Government, 2014). This is promoted primarily as a route through which local areas – "community" typically refers to the geographic area around a development, although this need not be the case – might benefit from associated economic opportunities[19].

An important clarification in the work of Bristow et al. (2012) concerns the definition of "community", and so the geographic or collective group or area which is impacted by the development of windfarm, and so is in receipt of "community benefit" payments. This notes that this definition is typically concerned with the "affected community", but that this was typically characterised firstly, by the wind energy developer themselves, and secondly, as a "community of place" (Bristow et al., 2012, p.1112):

> "the geographical community (or communities) around the development site, and deemed to be directly affected by the development, mainly in terms of direct visual effects. Pragmatic institutional boundaries are widely used: thus in the vast majority of cases, eligibility to receive community benefits is usually restricted geographically to residents or groups within designated community council areas contained, or having close visibility of, the wind farm concerned"

They also note that as the levels of community benefits have increased, there is increasing pressure to broaden the scope of "community", and move towards wider constituencies, such as "communities of interest" who are perhaps more distant from the

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[19] In the forward to this consultation, the Minister for energy, Enterprise and Tourism, Fergus Ewings writes, "We need to bring community energy in from the margins of energy policy to make it the central tenet of our future energy systems, where it has the potential to transform local economies...Community energy systems can play a pivotal role in sustaining our communities.. with all the associated economic and social returns" Scottish Government (2014, p.1).

development. Bristow et al. (2012) notes that increasing the complexity of the definition of community may lead to scope for conflict between such communities and institutions.

There are however three major assumptions of the analysis in Paper One, which are critical for the impact of any new energy development, particularly one which has significant local or community ownership. First, Paper One assumes that there is no opportunity cost to the local economy from the investment in the onshore windfarm. Monies for this investment are assumed to be borrowed and so the community "trust" is still able to make payments, while ownership receipts are net of interest and capital repayments on the borrowing. Were the investment to come directly from charitable funds themselves, with a commensurate reduction in the funds available for existing investment or spending, this would need to be taken account.

Second, the retention of the incomes in the local economy and the ways in which such retained incomes are deployed will clearly be critical for the economic impact of a given level of ownership profits (a point also noted by Munday et al. (2011) as discussed in Section 4.4). Paper One considers additional incomes accruing to households and the Charitable Trust, which are assumed to retain and respend these in accordance with the pattern of household and local government spending as given in the base year SAM. Although a reasonable assumption, this is untested: for instance, future work could examine the specific ways in which Trust incomes are spent (as opposed to retained in a "rainy day fund" or similar), and secondly, the extent to which community expenditure is made locally and how this differs from local government spending as a whole. Further, a survey of planned (*ex ante*) and actual (*ex post*) expenditures could sharpen the analysis further.

For the wider impacts of "community" energy developments in Scotland, it has been estimated that meeting the 500MW capacity target could lead to gross income for project owners of between £1.3 and £2.2 billion (Allan, 2014). To understand the consequences of this income for local economies it would be necessary to know much more about the ways in which owners spend the additional incomes received. Anecdotal evidence suggests a high propensity to spend such incomes, but a low propensity to spend on locally produced goods so that, for example, impacts on Scotland may be significantly greater (in absolute terms) than those on the host locality.

Finally, we assume that the electricity generated in Shetland is exported to the mainland Great Britain electricity grid, and none is consumed locally. Again, this is a reasonable assumption for this particular project, however, were the electricity to be used locally it would transform the nature of generation on the Islands and could displace (some) existing electricity generation. This critical assumption – although not directly relevant for Paper One – is crucial for the assessment of the contribution of Paper Two, to which we turn in Chapter 5.

Returning to the objectives of energy policy outlined in Chapter 1, we recall the four goals as: economic development, reduced emissions, improved security of supply and affordability of energy. On these goals, it could be argued that increasing community energy would contribute to economic development, perhaps particularly reducing inequalities of economic outcomes between places. For example, rural areas – which tend to have lower GDP per head – are likely to see more renewable development than urban areas. Allied to distribution of additional incomes to households across the income range, community energy could contribute to the economic ambitions of energy policy. The environmental benefits of increasing renewable energy production would appear to be largely uncontested, particularly if accompanied by a reduced use of more-polluting fossil technologies to cover periods when renewable energy was unable to meet demands. If policies to encourage community involvement in renewable energy spur additional renewable energy developments, these benefits are likely to be amplified.

5 The modelling of new biofuels activities

As described in Section 3.2.2, there has been a rapid increase in the amount of biofuels produced in the first decade of the 21st Century. Globally, the production of biofuels increased by 375% between 2001 and 2009. In the UK, the Road Transport Fuels Obligation (RTFO) started in 2008 and mandated that an increasing share of transport fuels sold in the UK be met from biofuels[20]. Biofuels have been promoted for a number of reasons, including their economic impact. As the discussion in Chapter 1 made clear however, these changes to the energy system – such as the pattern of production and consumption of fuels – will have consequences not only in the energy and transport systems, but on economic and environmental systems.

Perhaps most obviously, there is expected to be environmental improvements from this policy. While we will briefly discuss below whether these environmental benefits have been realised from conventional biofuels, there appears a strong environmental case for focusing on transport as part of a policy to reduce emissions. Transport is, for instance, responsible for around one-third of all greenhouse gas emissions in the UK, second only to emissions from energy supply. While emissions from both have fallen since 2008, the energy supply industry has seen emissions fall by 16% while emissions from transport have fallen by 7%. Indeed, since 1990, emissions from transport have fallen by only 2.4% for the UK (Table 3 in Department of Energy and Climate Change (2014a).

While there may be expected to be environmental consequences of this change, the economic impacts are uncertain, and have been an area of considerable analysis. There have been a number of applications of "fixed-" and "flex-price" economic modelling to the *ex ante* economic impacts of new biofuels production. Paper Two reviews these

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[20] In the first year of its operation (2008-9) large suppliers (i.e. those providing more than 450,000 litres of fuel) were required to provide RTFO certificates for 2.5% of their total fuel supplied, or pay a buyout price of 30 pence per litre. Certificates are awarded to producers of "sustainable" biofuels, creating a supply of certificates. Certificates can be traded, creating a market for these. In the most recent year, the obligation has increased to 4.75% of the road transport fuel supplied to the UK market. There are improving "traceability" for the sources of biofuels produced for the UK market since the first year (Department for Transport, 2015)

and suggests “best practice” for the use of such models to the application of new biofuels activities. Paper Two acknowledges that it is not the first to describe the differences between IO, SAM and CGE models or to summarise the limitations of the assumptions typically employed in each (such papers include Koh et al. (1993); West (1995); Partridge and Rickman (1998, 2010)). The major contribution of the paper to the literature is in identifying what should be considered as “best practice” in future multi-sectoral economic modelling of biofuels.

There are four elements to Chapter 5. Section 5.1 describes the technical details of biofuels, including the distinction between first-, second- and third-generation technologies. Section 5.2 discusses some of the potential consequences of new biofuels, both intended and unintended. Section 5.3.1 describes the (necessary) assumptions of “fixed-price” modelling and how these limit the appropriateness of this modelling approach, and the features of CGE models which suggest they would be would be appropriate for modelling biofuels. Section 5.3.2 then considers four particular aspects which are central to the appropriate modelling of biofuels.

5.1 What are biofuels?

“Biofuels” refer to fuels that are produced from biomass sources. These could be solid (e.g. bio-char), liquid (e.g. bioethanol or biodiesel) or gas (biogas) (Charles et al., 2007; Demirbas, 2009). Total biofuels production is largely comprised of bioethanol and biodiesel, which are “first-generation” biofuels. This refers to their production from biomass sources, such as sugar cane, sugar beet, maize in the case of bioethanol, which are traditionally grown for human consumption (i.e. are “comestible”) (Charles et al., 2007).

That all these crops have to be grown on agricultural land is obvious, and that without “excess” land (i.e. usable land for crops, not currently used) any crops grown for biofuels must necessarily reduce the land available for the growing of crops for non-biofuel purposes, such as for (animal or human) food or as inputs to other industrial production. Brennan and Owende (2010) report that 1% of the world's available arable land is used to produce biofuels that provide 1% of transport fuels around the world. To be clear, in the absence of over-capacity of agricultural land, a clear consequence of the development of first-generation biofuels is the consequential reduction in agricultural land available for other purposes.

Additionally, first-generation biofuels are inefficient, only producing a useable biofuel with a fraction of the energy used in the cultivation, harvesting and processing of the feedstock (Charles et al., 2007). Production of the biofuel is likely to occur within the same region as the biomass feedstock is produced as transporting biomass long distances is prohibitively expensive. Therefore, the production of new biofuels is likely to require significant new investment in a high number of local (i.e. within a certain distance of where the crops are grown) production facilities, before being transported to onwards markets as the final product (Low and Isserman, 2009).

Second-generation biofuels are those "derived from feedstocks not traditionally used for human consumption" (Charles et al., 2007, p.5738). These can use a range of plant matter, including grasses, wood, or agricultural waste (Brennan and Owende, 2010). Two common processes include using enzymes to convert the cellulose in the biomass product to ethanol or using "pyrolysis" – heating in the absence of oxygen – to produce liquid bio-oil or syngas. An added advantage of these processes is that the energy produced is higher per unit of feedstock. Despite their apparent benefits relative to first-generation biofuels, second generation technologies have been criticised for lacking a commercial scale of activity (Brennan and Owende, 2010).

In recent years, there has been much research interest in so-called "third-generation" biofuels, that is biofuel derived from marine algae (e.g. Brennan and Owende 2010; Singh et al. 2011). These algae have certain unique properties, compared to first and second-generation biofuels (Brennan and Owende, 2010). First, they can be grown all year round. Second, they need less water than terrestrial feedstocks. Third, they can be cultivated in existing water areas, not using existing arable land[21] . Such fuels have been argued to be a "viable alternative energy resource devoid of the major drawbacks (food-fuel competition, land-use change, etc.) associated with first- and second-generation biofuels."(Singh et al., 2011, p.150).

5.2 The possible consequences of biofuel production

Charles et al. (2007) summarise the key drivers of policy in support of biofuels. Two of these are climate change/reducing emissions and energy security[22]. These are two of the specific goals for many energy policies discussed in Chapter 1. In this section, we give a brief summary and critique of these non-economic consequences of new biofuels production.

Beginning with the policy focus on reducing emissions, it is estimated for instance that in 2011, 18.1% of CO2 emissions in Scotland came from road transport (Scottish Government, 2013). Biofuels are a renewable resource, offering the promise of the emissions in the burning of the fuel in transport being offset by the carbon sequestrated by the growing of biomass feedstock. In the parlance of Searchinger et al. (2008) the "carbon sequestration effect" credited to biofuels was argued to be greater than emissions during the growing, refining and burning stages of biofuel cycle.

This theory is however undermined by influential studies of the changes created by new biofuels production, the first of which was Searchinger et al. (2008). They found that higher prices for biofuels encouraged the conversion of land from current patterns of usage to growing more biofuels. As that land (not used for growing biomass) would currently sequester carbon, diverting agricultural land to growing biomass would only

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[21] Other advantages over first and second-generation biofuels include their higher oil content and faster growth rates, they can sequestrate more CO_2, do not require pesticides, also produce valuable co-products as waste, such as proteins or residual biomass (Brennan and Owende, 2010).

[22] The other two were "employment in the agricultural sector" and "resource potentials". Given that the economic (including employment) impact in all sectors, and the agricultural sector is the focus of the economic modelling work which comes later, we leave this point until the later sections.

reduce emissions if the “carbon benefit of land” is increased. They state, “Proper accounting must reflect the net impact on the carbon benefit of land, not merely count the gross benefit of using land for biofuels.” (Searchinger et al., 2008, p.1238). The “proper accounting” of the changes to the available factors of production is also important for the economic impact of new biofuel production, as we will see in Section 5.3.1.

Through reducing the need for imports of fossil fuels, it has been argued that increasing the use of biofuels could improve energy security, and indeed national security (Charles et al., 2007). One aspect of energy security is the extent to which energy is imported. On this measure, increased biofuels for transport would only serve to improve this measure of energy security to the extent that biofuels are produced from indigenous resources and that fossil fuels for transport are currently imported. In the UK, for example, in the first year of the RTFO, only 8% of the biofuel used was produced in the UK (Renewable Fuels Agency, 2009). The latest figures suggest that about 32% of the petroleum used in the UK is “domestic” in origin (Department of Energy and Climate Change, 2014b).

Clearly, there are other dimensions of transport fuel security including, but not limited to, the resilience of UK supply to changes in availability from different (non-UK) sources of fuels, the scale of transport fuel storage, and the delivery of fuels across the UK. It is notable that the major supply disruption to transport fuel supply in the authors lifetime was caused in September 2000 by protests against the rate of tax on fuels leading to blockages at fuel depots and preventing the distribution of fuel to forecourts (House of Commons Library, 2011).

Assessing the economic consequences of new biofuels production requires the use of economic models, particularly models which have a strong sectoral basis. This is required both to capture the focus on the agriculture sector and the economy as a whole, and also because there are likely to be sectors which will gain as a result of new biofuels production, as well as others that could “lose”. Paper Two argued that it is likely that the economic impact of new biofuels production would depend upon a number of factors, including: the specific biomass feedstock and production technology employed; its embeddedness to the rest of the economy (which could include local ownership of the facility); the extent to which new activity is created; and the structure and characteristics of the economy (Allan, 2015).

5.3 The contributions of Paper Two to the academic and policy literatures

There are two inter-related contributions that Paper Two makes to the academic literature. These are first, a detailed evaluation of the multi-sectoral modelling literature on the economic consequences of biofuels production, and second, identifying the critical issues in model design and use in this area, i.e. as an economic modelling "best-practice" guide. Each of these two points are described in the two Sections that follow.

5.3.1 Evaluation of "fixed-" and "flex-price" modelling approaches

The key points of the evaluation of IO/SAM and CGE applications to biofuels modelling are summarised in Table 5. This reproduces Table 5 in Allan (2015, p.15), and is intended to frame the discussion of the strengths and weaknesses of the different modelling approaches to the particular issue. As described in Paper Two, points 1-4 in the table refer to areas in which IO/SAM models have a relative weakness to CGE methods, while the latter two are where IO/SAM methods have a relative strength. In the rest of this Section, we describe the specific rationales for our identification of each point as either a relative strength or relative weakness.

First, the specific immediate consequence of new biofuels production would be on the supply-side of the economy. IO/SAM papers need to calibrate a demand shock to recreate the aspects of this new biofuels shock – and we return to this below – while in

Table 5: Strengths and weaknesses of “fixed-” and “flex-price” approaches for modelling the regional impact of biofuels production

	IO/SAM		CGE
Relative weakness	Supply shock modelled as a demand shock	Relative strength	Accommodate both demand and supply-shocks
	Supply of all factors of production, including land, is typically assumed to be infinitely elastic at the existing market price		Availability of factors of production modelled explicitly, with markets determining the price
	Sectors do not compete over factors of production		Factors of production move to sectors where the return is greatest
	Welfare impacts cannot be compared		Welfare impacts of changes can be evaluated
Relative strength	Demand for local resources explicitly modelled	Relative weakness	Difficult to parameterise and introduce new sector
	Link between new demand and aggregate impacts is estimated using accepted methods		No standard methodology makes assumptions in the model structure (e.g. parameterisation, closure rules, and behavioural assumptions) crucial for results

a CGE environment, an increase in supply would lead to a fall in price and expansion in economic activity. This suggests a relative strength for CGE analysis.

Second, the consequences of changed demand for usable factors of production will not be endogenous in IO/SAM models, but will be in CGE approaches. As we saw above, where the IO/SAM approach assumes an entirely passive suppy-side, explicit supply constraints can be imposed in a CGE context. Changed availability of land resources, for instance, will drive changes in the price of land, which will change the use of land between different activities, i.e. towards those activities to which the return to land is greater - and assuming that land can change its use such that this can occur.

Much of the IO/SAM analysis of new biofuels which is surveyed in the paper demonstrates an awareness of this specific limitation of the technique. Some attempt to adapt the "fixed-price" method to produce results which emulate the existence of such supply constraints in the specific applications. Perhaps the most straightforward way to consider this consequence in an IO system is to constrain the sectoral output of the factor-using sector, such as agriculture, so that a change in demand for its output will not have an impact on its own output. This is done by Low and Isserman (2009), for example. Others, such as Swenson and Eathington (2006b); Kulišić et al. (2007); Van Dyne et al. (1996) introduce a negative demand shock which has the consequence of making the output for the identified supply-constrained sector remain at its initial level. Cunha and Scaramucci (2006) make no offsetting shock, which is perhaps a reasonable assumption given the specifics of the availability of land for biofuels in Brazil, e.g. with underutilised agricultural land.

It seems more appropriate, however, to try to capture such changes using a model which endogenises the (specific characteristics of the) supply-side of the economy, so that changes in the supply and use of any factor of production can be made explicit, rather than being assumed. As the paper asks, "if supply constraints on specific (non-produced) factors are a feature of the economy, how does this determine the maximum output for each sector?" (Allan, 2015, p.628). In some cases it might be appropriate to assume that all such factors are currently fully exploited, while in others it may not. Part of the skill of the economic modeller is to identify the appropriate modelling technique which can be used in particular contexts, and this point alone suggests that the most useful model for understanding the consequences of new biofuels production would be one in which the properties of the land, and other, factors of production are made explicit.

Interestingly, among the single-region or national CGE modelling of new biofuels identified in Paper 2, the treatment of land in aggregate differed. This highlights the lack of a general common "structure" to all "flex-price" models, first discussed in Section 2.3. In Giesecke et al. (2007), for instance, land is used in agriculture and is fixed in aggregate, however in others, e.g. Dixon et al. (2007) and Gehlhar et al. (2010) there is no explicit land constraint. While this omission appears important, it could be a feature of the agricultural sector in the respective countries (Giesecke et al. (2007) in Australia and Dixon et al. (2007) and Gehlhar et al. (2010) for the USA) and each could, in principle at least, be an appropriate treatment of land in each respective application.

Third, and linked to the point above, the most appropriate model should be one in which factors of production – including usable agricultural land – are usable across different activities in response to their profitability in those alternate uses. Farmers may, for example, switch the use of land to other sources, depending on the profitability of the change and the costs of changing the use of land. As outputs change, the relative prices of goods will alter, causing there to be impacts on other sectors endogenous to the system. Some sectors may gain, as their output crowds out other economic activity. These impacts could be exogenously imposed in IO/SAM systems, however in a CGE system they would explicitly arise endogenously, and arise from the specification of the models, rather than being imposed by the modeller (who would set the values of key parameters that influence crowding out, but would not specify the extent to which activities would be affected).

Fourth, the results of CGE systems produce sufficient information for the analyst to compare the welfare of agents in the economy. Such information is not available from IO/SAM analysis. It could be important for policy to assess the welfare consequences of new biofuels policies – in addition to the economic impacts alone – and so underscores the additional benefits of a CGE approach to this case.

5.3.2 What does a model exploring the impacts of biofuels require?

It is the position of Paper Two that fixed-price methods have some uses for estimating the potential economic impact of biofuels production. However, some of the assumptions of these models – partially recognised in some of the analysis which has used these models to date – makes them less powerful than “flex-price” models for this specific modelling activity. In this section, we describe the specific features of “fixed-price” models which makes their application to biofuels particularly challenging.

We summarise the standard assumptions in IO and SAM modelling in Section 2.2 earlier. These were: 1) an entirely passive supply side, 2) the separation of exogenous and endogenous accounts, with a consequent lack of crowding out, and 3) fixed technical coefficients in production.

Additionally, Paper Two argues that any economic modelling of new biofuels production will need to take account of four specific issues. These are that:

- Land is fixed in aggregate but mobile between uses
- Current economic activity could be displaced
- A new sector typically will be introduced into (and becomes part of) an existing economy
- That the impacts will initially be on the supply-side of the economy

We consider each of these in turn. First the specific factors of production necessary for biofuels production will be a constraint on biofuels production. It is clear, for example, that there is a limit to the amount of agricultural land suitable for growing crops for (first-generation) biofuels. Additionally, only a subset of all agricultural land could be used for producing biomass as crops require water, productive soil, fertiliser and access to local markets (Low and Isserman, 2009).

All demand-driven IO and SAM modelling has a straightforward treatment of labour and capital, assuming that these respond entirely passively to the level of demand. This can be justified in some applications as either representative of a national economy with extensive underemployment and no constraint on its ability to access finance. Alternatively, these assumptions could be sensible for a small regional economy in which the available labour force was open to migration to the region in response to any increase in the demand for labour, and where regional investment was similarly unconstrained through access to capital markets outwith the region.

Agricultural land on which to produce biomass, on the other hand, is not mobile across regions and is highly unlikely to be currently unused. Ignoring the option of "land reclamation", which is unlikely to – even if technologically possible – provide appropriately usable agricultural land, we might sensibly consider the land resource for biomass as fixed.

Second, biofuels production could displace existing economic activity. On the demand side, expenditure will switch towards biofuels, the cost of which would be the lost expenditure on existing fuels and the activity supported by that spending. If biofuels are imported, while existing fuels were domestically produced, this cost could be significant. On the supply-side, land which might be used for biomass could also be useable for different types of agricultural production. The use of land for biomass would necessarily reduce the output of the other land-using activity, and be a further cost of new biofuels.

We saw in Section 4.2 how “fixed-price” methods explicitly deal with the introduction of new economic sectors. This requires information on the new sector’s embeddedness into the economy through its local purchases and sales. The approach has the benefit of being straightforward – particularly where the technologies are known and the possible use of the products are clear. Paper Two, however, describes a range of approaches used in the CGE literature for introducing new sectors, some of which appear more useful than others.

Up to this point, we have typically used IO/SAM modelling to describe the consequences of demand-side disturbances. When considering biofuels production, however, the modeller must remember that the new production sector will increase the supply of biofuels, lower its price and potentially stimulate economic activity. The model being used to explore the “knock-on” consequences of new biofuels production therefore, must be able to simulate the consequences of this lower price, and the resulting supply-side stimulus.

6 The impacts of expenditures on new energy capacity: model specification, “legacy effects” and local content

This chapter describes the usefulness of economic modelling approaches for understanding the consequences of demand disturbances – which are the focus of Papers Three and Four. Specifically, the demand disturbances modelled are the set of demand-side expenditures associated with the development of new (planned and projected) marine energy (i.e. wave and tidal) capacity in Scotland. Papers Three and Four employ a “flex-price” (CGE) model for Scotland to explore the system-wide consequences these expenditures.

The sets of expenditures has both a sectoral dimension – reflecting expenditures across industries in Scotland – and a time dimension. In both papers, expenditures increase in line with the addition of new marine energy capacity until a specific measure of installed capacity (e.g. expressed in terms of MW) is reached.

The scale of expenditures considered in both analyses mean that each has the characteristics of mega-projects, i.e. projects with expenditures which are large in relation to the scale of the host economy. We might expect that these could have system-wide impacts through, for example, tightening the regional labour market by increasing the demand for labour. The scale of economic impacts will be affected by, *ceteris paribus*, the extent to which expenditures are made within the Scottish economy – i.e. the “local content” of these expenditures – while, we show that the scale and timing of impacts depends on model specification. Specifically, we show that the assumptions of IO modelling lead to the scale of impacts during the period of expenditures being overstated relative to when a CGE model is used. Specifically, we find that the IO assumption of a passive supply–side explains this result. Further, we find that there are economic impacts which arise as a result of temporary demand-side disturbances in a CGE model, but continue after the disturbances themselves have ceased. We term these “legacy effects" in these papers, and note in Paper Four that these arise irrespective of whether agents are modelled with myopic or backward-looking behaviours.

Chapter 6 is ordered as follows. Section 6.1 considers the major expenditures associated with developing new energy capacity, and the scale of expenditures associated with the specific capacity additions considered in Papers Three and Four. This notes the local content assumptions used in these papers, which show the extent to which sectors in the Scottish economy may experience the (direct) spending on the additional capacity in Scotland. Section 6.2 describes the issue of local content in energy policy, drawing from examples of local content requirements across the world, and how the issue of local content – and the related, but distinct notion of "supply chain" – has featured to date in Scottish renewable energy policy.

Section 6.3 describes the CGE models of Scotland used in Papers Three and Four to examine the set of demand disturbances. This gives the details of the model specification and databases used in each of these papers (and notes the difference between the model features in each paper).

Section 6.4 discusses the specific academic and policy contributions of papers Three and Four. In turn, these are: a robust exploration and explanation of the differences in total (cumulative) results from IO and CGE modelling of sets of temporary demand disturbances as well as the identification of "legacy effects" and the model specifications which gives rise to the finding of economic impacts which follow the end of temporary demand-disturbances (Section 6.4.1). Section 6.4.2 discusses how Input–Output analysis could be used to explore the system-wide consequences of a set of demand disturbances, but notes the general neglect of time from IO analysis, and how analysts have used of the "rounds" of the multiplier to distribute impacts over time and the problems of this approach. Section 6.5 sets out how the approach of Papers Three and Four can be used to understand the additional impact of changes in local content from renewable energy expenditures.

6.1 The expenditures associated with new renewable capacity, and local content

We saw in Section 4.1 that there are several potential channels through which the addition of new renewable energy capacity might impact on the local economy. While the ongoing transfers between the operational facility and the local economy, such as through Community Benefit, or other financial links, were central to the discussion in Chapter 4, and the contribution of Paper One, in this section we focus primarily on the expenditures at the pre-operational stage. Earlier we noted that: total pre-operational expenditures are likely to be a significant; they are temporary in nature; and, that only a small portion of the total expenditures may be spent within the local economy.

We start by noting the scale of the pre-operational expenditures associated with development of new technologies. The potential for the significant expenditures around new development of capacity to create economic impact during the construction phase is also central to the reports on the UK's offshore energy potential (Offshore Renewable Energy Catapult, 2014) and the economic impact of a new nuclear facility on Anglesey (BBC News, 2015b).

That major expenditures during the pre-operational stage may lead to economic impacts is not a recent discovery. Tom Johnston (the Secretary of State for Scotland during the Second World War) noted – when debating The Hydro Electric Development (Scotland) Act in 1943 – that, "the Bill will give considerable employment, direct and indirect, in coal, iron, steel, cable-making, electrical engineering, cement, house and civil building works, and contracting. On the basis of the experience of the Central Electricity Board, the operations of the Board on an expenditure of £30 million should give employment, direct and indirect, of the order of 10,000 men for a number of years" (Hansard, 1943).

Paper Three, for instance, notes the major expenditures projected for the development of new marine capacity in Scotland. These are given for three scenarios of capacity development, ranging between a total installed capacity by 2020 of 479MW and 1,982MW by 2020 in the "Downside" and "Stretch" scenarios respectively (Sgurr Energy and IPA, 2009). These two scenarios project an associated global expenditure (e.g. the total amount spent on developing this capacity between 2010 and 2020) of £1.3 billion and £4.7 billion, respectively. The higher amount here is roughly comparable to three times the cost of building the new Queensferry Crossing of £1.45 billion (BBC News (2014)).

Paper Four models the impact of the set of expenditures associated with the development of further marine capacity in the waters off Scotland. Specifically, it begins with (global) expenditure – estimated by the UK's Crown Estate (The Crown Estate (2011)) – of £5.4 billion over the 11 years between 2010 and 2020 associated with the development of an installed capacity totalling 1.6GW (1,600MW).

We turn now to the second issue identified earlier, that of the share of total expenditures on new capacity that is supplied by the local economy. There is anecdotal evidence that for additions to energy capacity, only a small portion the global expenditures will be spent locally. This is important for the economic consequences of such expenditures as only local expenditure creates additional local demand for goods and services during the (perhaps brief, and likely temporary) period of construction and installation. Roberts (2011), for instance, reveal that 32 per cent of the £381 million budget for development, manufacture, construction and operation of the Robin Rigg windfarm was spent in the UK. The share of expenditures under each category varied: for example, there was no UK content in "Turbine manufacture". This category comprises 37% of all expenditures. There was however, respectively, 100% and 56% of expenditures sourced in the UK for the "Project management" and"Installation and commissioning" categories.

The extent of local content is also likely to vary with the size of the economy, i.e. *ceteris* *paribus* a larger economy will be more likely to produce appropriate goods and services necessary for such activities[23]. We saw earlier that Munday et al. (2011) reported that there is limited scope for the inputs to the construction phase of windfarms to be sourced in Wales. For the development of new onshore wind capacity in Northern Scotland, Okkonen and Lehtonen (2016) find that around 14% of pre-operational expenditures are made in the local economy. Similarly, looking at the areas most proximate to the Robin Rigg development, Roberts (2011) report that 12% of all expenditures (roughly one-third of the UK expenditures) were made in Scotland and the North West of England in total. Looking at the more local geographies of Cumbria and Dumfries and Galloway (the areas closest to the development) only 1.6% of all expenditures were sourced in these areas in total.

Papers Three and Four both require the identification of the local (i.e. Scottish) share of global expenditures on developing marine energy capacity. A bottom-up approach was possible: rather than simply taking a share of global expenditures, the expenditures were taken from published reports stating the spending in different products/categories – which could be then matched with a sector of the economic models. Second, expenditure in each (detailed) category is adjusted by a factor to remove the non-Scottish share of spending on this category.

In Paper Three, the "category-specific factor", β_j, was used to adjust from global expenditures on each category (j) to that which was spent in Scotland. These were taken from Sgurr Energy and IPA (2009) and were assumed in that report to remain constant across all years of expenditures. Table 3 in Gilmartin and Allan (2015) shows that the share of local expenditure on each category ranged from 11.0% for "Mechanical plant" category to 97.5% for "Logistics base". Allan et al. (2014a) used the same procedure

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[23] As well as differing across categories of costs, is also likely that the share of local content will differ by technology. A recent report on small-scale hydropower for Wales however estimated that between 70 and 90% of Construction expenditures would be made in Wales, and between 50 and 70% of Industrial and mechanical expenditures. For small-scale turbines, the report assumed 80% of costs would be made in Wales, while for large turbines (with an individual capacity of 499kW) all expenditures would be made outside Wales (Bere et al., 2015).

to calculate expenditures related to those developments in Scotland as demand for Scottish goods and services. The bottom-up approach used in that paper generated an overall local content for pre-operational expenditures of 42%.

We will see in the next section how the issue of local content is manifested in policy actions, while in Section 6.5 we show that one of the contributions of Paper Three is a new approach – using the CGE model of Scotland – for understanding the consequences of changes in the local content of individual categories of expenditures on marine energy developments.

6.2 Policy for local content in renewable energy

Considerable policy focus has emphasised the impact of "local content" of the expenditures on renewable energy capacity. Kuntze and Moerenhout (2013) describe the instances of "local content requirements" (LCRs) in renewable energy around the world[24]. A higher share of expenditures made in the region or nation has been proposed as a way to maximise the economic opportunities which could arise from the development of energy capacity. As Kuntze and Moerenhout (2013) notes, LCRs may be based on political, rather than economic, motivations. Additionally, while it is possible that LCRs could increase domestic employment, for example, there may be cost advantages from importing technologies, for instance. We discussed such tensions at the heart of energy policy in Chapter 1.

Kuntze and Moerenhout (2013) describes LCRs in Ontario of 50% in 2012 for wind and 60% for solar capacity greather than 10kW, how Quebec had LCRs for wind energy since 2003 beginning at 40% for the first 200MW and increased to 60% in later years for further capacity developments. They also describe voluntary LCRs in Spanish

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[24] (Kuntze and Moerenhout, 2013, p.5) define local content requirements as "policy measures that require foreign or domestic investors to source a certain percentage of intermediate goods from local manufacturers or producers. These local producers can be either domestic firms or localised foreign-owned enterprises."

provinces of upwards of 60% and LCRs linked to Feed-in Tariffs in other EU states, including Croatia, Italy and France, and an LCR in Brazil of 60% for wind energy. As of 2012, Kuntze and Moerenhout (2013) note LCRs for wind in China of 70%, 50% in Quebec, 60% in Brazil and 70% in Spain. Local here is taken to be at the national level, but as (Kuntze and Moerenhout, 2013, p. 5) notes, "the policy measure is by definition a performance requirement that can be enacted at the state, sub-state or regional level".

While there are no stated local content requirements in Scotland, there has been considerable policy thinking around the "supply chain" opportunities for current Scottish firms to secure contracts for work in renewable energy. The 2009 report for the Scottish Government's Marine Energy Group (MEG), for instance, identified that for a 50MW marine energy project in Scottish waters;

> "as much as 53% of expenditure on such a project would be retained in Scotland" ... "MEG believes that the retained Scottish proportion could rise significantly, if subject to proactive stimulation over time. The report highlighted that notable areas of significant expenditure where the contribution from the Scottish supply chain is expected to be relatively low include: mechanical plant (e.g. hydraulics, turbines); electrical plant (e.g. generators, switchgeear); cables, umbilicals and communications, grid connection; and installation vessels" (Forum for Renewable Energy Development in Scotland, 2009, p.43).

More recently, the 2014 "National Marine Plan" noted that the "Economic benefits from offshore wind, wave and tidal energy developments [are] maximised by securing a competitive local supply chain in Scotland" (Marine Scotland, 2014, p.82). Additionally, an earlier National Renewables Infrastructure Plan (Scottish Enterprise and Highlands and Islands Enterprise, 2012) sought to bring together a coherent set of investments which would support economic development from the creation of renewable energy capacity in Scotland, including public investment in, e.g. harbour and other sites, which could encourage further industry clustering around sites serving renewable developments.

Roberts et al. (2014) examines the "supply chain" for UK offshore wind development, by considering the "potential UK expenditure" under broad categories of the expenditures associated with developing this technology. By examining the availability of individual elements of an offshore device that might be met by UK suppliers, this specifically relates to the extent to which there will be "local content" to these expenditures. In that report, the scale of expenditure on each category that could be secured from UK firms is multiplied by that category's share in overall device expenditures to give a measure that was termed, "size of the UK opportunity". This implies that policy should focus on improving the "local" (in this case, UK) share of expenditures from those categories which have a greater share in overall device cost.

This approach neglects the extent to which the additional economic impact generated by expenditures in different categories might generate throughout the economy. For instance, there may be quite different multiplier impacts for different categories of wind energy development due to the way in which the production methods for each category are embedded within the rest of the economy. We return to this issue in Section 6.5.

6.3 Modelling temporary demand shocks in a CGE framework

The specific focus of papers Three and Four is the introduction of expenditures on marine energy developments as a set of temporary demand-side disturbances to an appropriately specified CGE model of Scotland. The model features a dynamic updating specification showing the series of equilibria for given levels of factors of production, and can be used to explore the scale and timing of the economic impacts which accrue for the region in which the expenditures takes place (these expenditures in Scotland are described in Section 6.1). In both papers, the expenditures are assumed to start at a relatively low base and increase to a peak over a total of 11 periods in each case with the model run on with no further disturbance for a further 39 periods (Allan et al., 2014a) and 89 periods (Gilmartin and Allan, 2015) respectively. The response of the economic system in each paper is explained by the interaction of the specification of the supply-side with the behavioural responses of households and firms, i.e. whether these are “myopic” or “forward-looking”. Both assumed behaviours given rise to “legacy effects”, as we shall see in Section 6.4.5 and Section 6.4.6 later.

The major policy implications of these papers are that temporary demand shocks can produce impacts beyond the period in which the shocks occur. We term these “legacy effects”, (Allan et al. (2008); Gilmartin and Allan (2015); Allan et al. (2014a)) - that is, “economic impacts which persist beyond the period in which expenditures occur” (Gilmartin and Allan, 2015, p.2). Each paper shows that these effects can be quantitatively significant for the employment impact of demand-side disturbances. This is the first significant contribution of these papers, and is discussed specifically in Section 6.4.1, where the distinction between results from the CGE application, rather than an IO specification, is made clear.

We will see later in Section 6.4.3 how conventional IO modelling would consider these expenditures. This clarifies the additional contribution of using a CGE model to examine the economic impact of such expenditures.

Section 6.5 describes the second contribution of these papers, that is the development of a new approach for evaluating the impacts of changes in the local content for renewable energy investments. This Chapter continues by describing the AMOS CGE modelling framework and the specific features of the model used in Papers Three and Four.

6.3.1 Introduction to AMOS

The original AMOS framework was developed in the 1980s[25]. It was first developed to include a supply-side rooted in microeconomic behaviours into regional economic models, and so to move these models away from the previous assumptions of passive supply (such as that assumed in regional IO models) (Harrigan et al., 1991). Gillespie et al. (2001, p.127) writes that while IO multiplier techniques have uses in quantifying the system-wide impacts of changes in employment in specific sectors, their assumptions mean that these models have limitations, and that "over the last decade and a half there has emerged a regional computable general equilibrium literature which is better able to address these issues". Recent developments in CGE modelling can be found in Partridge and Rickman (1998) and Partridge and Rickman (2010).

AMOS is referred to as a CGE modelling framework as it features a "menu" of specifications which could be employed. Harrigan et al. (1991, p.424) writes that AMOS "encompasses a range of behavioural assumptions, reflected in equations wich can be activated and configured in many different ways". This gives the applications of the model considerable flexibility and also allows the user to perform robustness checks to the results of model simulations. For example, the assumed nature of wage setting and the operation of the labour market – whether for a regional or national economy – will be fundamental for the results of any model simulation, and so the user would be able to explore just how important model specifications are to model results (Harrigan et al., 1991). Separately, many parameters are required to operationalise the CGE framework and it may be impossible to estimate these empirically. Another feature of the use of the AMOS framework has been the use of sensitivity analysis to explore how important such assumptions are for results. Third, the AMOS framework, although typically used and developed with Scottish data, can be applied to other regions or

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[25] Harrigan et al. (1991, p. 424) notes that AMOS is an acronym for "a macro-micro model of Scotland" and describes AMOS as "...more of a modelling environment than a model. It provides a set of templates which transcends any single vision of the operation of markets in a small open regional economy such as Scotland".

nations for which the necessary benchmark dataset and parameter values exits, e.g. Pappas (2008) for the case of Greece and Learmonth et al. (2007) for Jersey (one of the Channel Islands).

6.3.2 AMOSENVI

In the quarter century since the development of AMOS, the model framework has been extended and developed in a number of ways. First, it has been extended to a two-region framework in which inter-regional migration adjusts the labour force in each region (e.g. Gilmartin et al. (2013)). Second, the level of sectoral detail at which model simulations can be run has expanded – with advances in computational and programming possibilities – from three-sectors (e.g. Gillespie et al. (2001)) to n-sector versions. Third, a version of the model in which there is considerable detail on treatment of energy within production – AMOSENVI – was developed, specifically to allow an estimation of impacts on energy-economy-environmental variables (Hanley et al., 2009) while the same framework has been applied to the UK. Recently, the backward-looking – or "myopic" – behaviours of households and industries in earlier versions of AMOS have been extended to the case where agents are forward-looking (Lecca et al., 2013). The forward-looking specification demonstrates that the long-run consequences of a permanent demand shock is identical whether agents have forward-looking or myopic behaviours, and it is only the transition path between the initial and final equilibrium which is affected by the assumed behaviours.

6.3.3 Applications

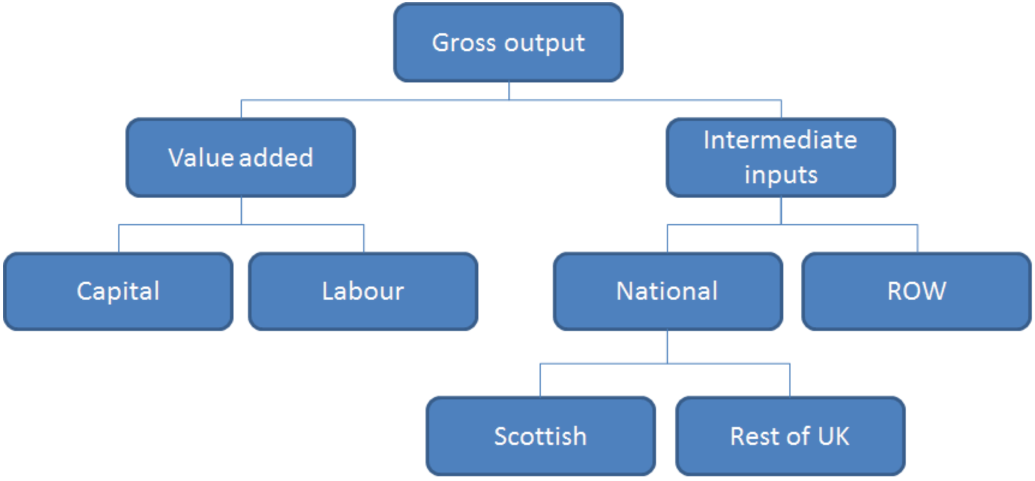
In Sections 6.3.4- 6.3.7 we detail the specific features of the version of the AMOS framework used in Papers Three and Four. The models in these papers share many similarities. The major difference in model structure is that Paper Four employs both, separately, myopic *and* forward-looking behaviours for households and firms, which we will see in Section 6.4.1 is critical for the timing of economic impacts from demand-side disturbances. The forward-looking version of the model, developed in Lecca et al. (2013), is applied in Paper Four to the case of temporary demand shocks. Both applications find "legacy effects" which are caused by the interaction of the demand disturbances and the supply-side of the economy. These effects would not arise in standard IO analysis.

6.3.4 Production and Consumption

A fundamental feature of the AMOS model is that producers are assumed to minimise costs typicallly subject to "nested" (i.e. multilevel) production functions. With substitution possible therefore between inputs, the specific inputs to each sectors' production alter with changes in the relative prices of inputs. Typically, while different production function relationships can be specified, a constant elasticity of substitution (CES) specification is chosen at each level, with the values of CES parameters taken from the appropriate CGE modelling literature. The nested production function is shown in Figure 1. At the highest level, value added and intermediate inputs combine in the production of sectoral output, with labour and capital combining in the production of sectoral value added. Local (i.e. Scottish, in these cases) intermediate inputs combine with inputs from the rest of the UK (RUK) and rest of the world (ROW), where imports are specified via an Armington link (Armington, 1969). This specification means that local and imported intermediate inputs are not perfect substitutes and are relative price sensitive.

With regards to demand for goods, in both papers, there are three transactor groups – households, government and corporations – and two exogenous transactor – the rest of the UK and the rest of the world. There are four elements of final demand: consumption, investment, government consumption and exports. Commodity markets are assumed to be competitive, and while financial flows are not explicitly modelled we

Figure 1: The multi-level production structure of the AMOS CGE model



assume that the interest rate is exogenously determined. In both papers, government consumption is assumed to be exogenous while exports are determined via an Armington link (Armington, 1969). The treatment of household consumption and investment differs in the myopic and forward-looking cases and is discussed in Section 6.3.7.

6.3.5 Labour market and migration

In both papers, a single Scottish labour market with perfect sectoral mobility is assumed, implying that workers are able to move costlessly between employment in any sector. Labour is therefore homogeneous, and there are assumed to be no skill or other barriers preventing firms expanding their employment from the available labour force. The nature of wage determination is important for the impacts of disturbances in a small open economy, such as Scotland. We described earlier how a range of options are available in the AMOS framework. In both Papers Three and Four, however, it is assumed that regional wages are determined in accordance with an econometrically paramaterised bargained real wage function (Layard et al., 1991). Under this specification, (real) wages are directly related to workers' bargaining power and therefore inversely related to the regional unemployment rate, i.e.:

$$ln\left(\frac{w}{cpi}\right) = c - 1.113\ln(u) \tag{3}$$

where w is the Scottish nominal (take home) wage; u is the Scottish unemployment rate, cpi is the Scottish consumer price index, and c is a calibrated parameter to ensure that in the base year of the simulation the model replicates the assumed initial steady-state equilibrium.

Migration is considered in the version of AMOS used, which is important given that Scotland is a small open regional economy, and thus, the labour force is not exogenously determined. For simplicity, we assume that inter-regional migration (i.e. to and from Scotland and the rest of the UK) is therefore the sole source of population change. In the models used in Papers Three and Four, migration adjusts in the same way; based on the model of Harris and Todaro (1970). Net migration is positively related to the (current) real wage differential, and negatively related to the (current) unemployment rate differential, between Scotland and the rest of the UK, i.e.:

$$\ln\left[\frac{m^S}{L^S}\right] = \mu - 0.08[\ln u^S - \ln u^R] + 0.06\left[\ln\left[\frac{w^S}{cpi^S}\right] - \ln\left[\frac{w^R}{cpi^R}\right]\right] \tag{4}$$

where μ is a calibrated parameter which ensures zero migration in the initial equilibrium; m is net in-migration; L is the labour force; u is the unemployment rate; w is the (nominal) wage rate; and cpi is the consumer price index. Subscripts S and R respectively denote Scotland and the Rest of the UK. The coefficients in the equation above specify the elasticity of migration with respect to unemployment and real wage differentials between Scotland and the rest of the UK respectively. These parameters are taken from UK econometric work (Layard et al., 1991)[26].

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[26] These parameters will clearly affect the scale of any migration response which is induced by changes to real wages and unemployment rate in Scotland. In earlier work, Allan et al. (2008) we explored the sensitivity of economic impacts to changes in these elasticities and found that making these values more inelastic the adjustment of migration would occur more slowly, lowering the immediate economic impact but extending the "legacy" effect which occurred.

6.3.6 Benchmark dataset and parameter values

In both papers, the model is calibrated on a Social Accounting Matrix (SAM) for Scotland from 2006. This SAM has twenty-five sectors/commodities in total, of which eight are directly affected by the increase the demand for their output. These were selected as being those "in which expenditures associated with the assessment, construction and installation of marine energy devices... are likely to be made" (Gilmartin and Allan, 2015, p.342). While the other seventeen sectors are not directly stimulated, they clearly are affected by the demand disturbance through linkages to the directly stimulated sectors as well as through changes in the relative prices of factors (e.g. labour) and goods, including their own output. The detailed sectoral aggregation is given in Table 6, where sectors 1 to 8 directly experience the expenditures related to new energy capacity and sector 9 to 25 do not. All sectors use CES technology assumptions in the production structure, with values set at 0.3 and all Armington trade substitution elasticities of 2.0. Parameters on household consumption and investment adjustment are discussed in the next section.

6.3.7 Dynamics of adjustment

Many CGE models are run only for static "periods", i.e. allowing comparative static analysis of the differences between initial and final equilibria. These equilibria could describe certain conditions of the availability of factors and therefore refer to "conceptual" periods of time. For instance, we shall see that Paper Five's examination of energy efficiency was principally concerned about the scale of "rebound" effects in the long-run, defined as the period over which labour and capital stocks have fully updated to their desired levels and so the economy is in a long-run equilibrium. Such conceptual and static analysis has value, for example in demonstrating the scale of economic impacts for alternative treatments of the supply-side of an economy, and so offer considerable use to the analyst wishing to compare IO results with alternative CGE model

Table 6: Sectoral aggregation for Papers Three and Four

Sector	Sector name	Sector in Scottish IO tables
1	Articles of Concrete	53
2	Mechanical Power	62
3	Electric motors and generators	70
4	Insulated wire and cable	71
5	Electrical equipment n.e.c.	72
6	Shipbuilding and repair	78
7	Construction	88
8	Architectural etc. activities	112
9	Agriculture, forestry, fishing and other primary	1 to 7
10	Food, drink and textiles	8 to 30
11	Gases, chemicals and pharmaceuticals	36 to 45
12	Plastic, rubber, glass and clay products	46 to 52
13	Other metal goods	54 to 61
14	Other machinery	63 to 69
15	Other electronic and precision instruments	73 to 76
16	Other manufacturing	31 to 35, 77, 79 to 84
17	Electricity	85
18	Gas	86
19	Water	87
20	Wholesale, retail, hotels and restaurants	89 to 92
21	Transport and communications	93 to 99
22	Banking, finance and real estate	100 to 105
23	Other private business services	106 to 111, 113 to 114
24	Public administration, education, health and social work	115 to 118
25	Other services	119 to 123

configurations.

The treatment of dynamics is also related to the nature of the demand-side disturbance being considered. If we were only interested in the lasting effects of a permanent demand-side shock, e.g. a step-change in preference for exports, for example, then the long-run analysis may be sufficient for our purposes. It would describe the position of the economy which would persist as a result of the stimulus, under the specification of the long-run in the model, in which there was a continuing (level) change in demand relative to the initial equilibrium. The transition between initial and long-run equilibria could be important as the "lifetime" of governments is typically fixed by elections. If impacts of policy decisions are felt beyond the lifetimes of governments, these might be heavily discounted in current policy thinking, so it could be useful to know the entire time path of effects from the "short run" (period 1) characterised by fixed sectoral capital stocks and fixed population, to the long-run equilibrium.

As Partridge and Rickman (2010, p. 1315) note, many CGE models do not have a time element to them, which has "likely contributed to their limited use in economic development policy analysis". As they note, static CGE models cannot show the time path of effects following a policy shock, and that dynamic versions of CGE models "give hope that these limitations can be overcome".

As was described in Section 3.2.3, Papers Three and Four explore the system-wide consequences of demand-side expenditures over a particular number of years. Specifically, we are interested in examining the impact of a series of temporary demand-side disturbances. The expenditures do not persist beyond 11 periods in each case, meaning that in the long-run, the economy returns to its initial equilibrium. There will be deviations away from the initial equilibrium which are caused by – i.e. directly result from – the temporary demand disturbances, but these will not give rise to a new long-run equilibrium. We must therefore run the model in a period-by-period setting to identify the impacts of interest. The nature of what drives adjustment between periods therefore is critical for the time path of any economic impact arising from these demand disturbances.

In both the myopic and forward-looking cases it is assumed that the economy is initially in long-run equilibrium. Without any disturbances therefore, the model would replicate its initial values in all time periods. What dictates the dynamic impacts of the model simulations is the interplay between household and investment behaviours. In both model specifications – myopic and forward-looking – we have the same treatment of migration, given above[27]. Recall that in each paper we have a demand expenditure

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[27] It is therefore a limitation of the model as currently configured that migrants base their migration decisions on comparisons of current differentials in real wages and unemployment rate. Earlier work has shown that if we were to assume a fixed labour force, i.e. no migration occurs, which would reflect an extreme situation where the costs of migration were always greater than the value of moving, that a legacy effect is still seen. However, the scale of these effects is much reduced (Allan et al., 2008).

which follows an assumed exponential increase in marine energy capacity and investment in the years out to 2020 in line with targets for energy capacity for this year, i.e. expenditures increase to a peak over a total of 11 years and then end (the disturbances are temporary). We can therefore focus on the response of rest of the economy and how it is assumed to adjust over time.

We begin with the "myopic" case – included in both papers. In this specification of the model, household consumption is a linear function of household real disposable income, while the sectoral composition of household consumption depends on the relative prices of domestic and imported goods. Household consumption therefore increases (decreases) as income rises (falls). The savings rate is exogenous and is given by the initial value from the SAM around which the model is constructed (see below). There is no assumed equivalence between regional savings and investment assumed in this or any version of the AMOS model – and is a standard assumption in many regional CGE models.

Investment in the myopic model is determined endogenously. It is assumed that the level of capital stock in aggregate and for each sector is fixed in the short run and that actual and desired capital stocks are equal in the initial equilibrium. Investment demand adjusts the level of capital stock in each sector, updating it between periods, and giving rise to a dynamic trajectory for aggregate and sectoral capital stocks. In each period, investment by sector i in period t ($\Delta K_{i,t}$) is equal to depreciation on existing sectoral capital ($\delta_i K_{i,t-1}$) plus a proportion (λ) of the gap between actual ($K_{i,t}$) and desired capital stock ($K^*_{i,t}$):

$$\Delta K_{i,t} = \lambda(K^*_{i,t} - K_{i,t}) + \delta_i K_{i,t-1} \tag{5}$$

Desired capital stock is given by cost minimisation of firms, taking into account existing commodity output, the nominal wage and the user cost of capital. Investment adjusts gradually therefore, consistent with the assumption of quadratic costs for adjusting capital stocks for each sector (Uzawa, 1969; Jorgenson, 1963). The speed of capital stock adjustment is initially set at 0.5, i.e. $\lambda = 0.5$, of the difference between actual and desired capital stock is made in each period, while the rate of depreciation (δ_i) is constant at 0.15 for all sectors.

Investment and household consumption behaviours differ in the "forward-looking" case[28]. Beginning with households, consumption decisions are made by households to optimise their lifetime utility subject to a wealth constraint. Forward-looking households first solve for the path of consumption over the simulation by intertemporal optimisation. For each period, the sectoral composition of consumption is allocated across local and imported goods via a CES function. There is a dynamic budget constraint assumed so as to ensure that households consumption does not exceed household wealth. As before, the rate of savings is exogenous and is not linked to investment.

Household consumption (C) in each period (t) is given by:

$$\frac{C_t}{C_{t+1}} = \left[\frac{PC_t \cdot (1+\rho)}{PC_{t+1} \cdot (1+r)}\right]^{-\left(\frac{1}{\rho}\right)} \tag{6}$$

where C is total consumption; PC is the aggregate consumption price; r is the exogenous interest rate and ρ is the pure rate of consumer time preference, i.e. households preference for switching consumption between periods. Since households consumption decision takes into account consumption prices – and in this "flex-price" system prices will rise with increases in demand – this will serve to switch consumption away from periods of higher prices. There is assumed to be a single, infinitely-lived household, which is able to switch expenditures between periods in this way.

The dynamics of investment in the forward-looking model are more complex than in the

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[28] Full details of the specification of the forward-looking model are given in Lecca et al. (2013) but we only present the treatment of household consumption and investment here as these are critical for the scale and existence of the "legacy" effects observed in the forward-looking model.

myopic case. It is specified consistently with previous work in this literature (Hayashi (1982) in which the rate of investment is a function of marginal q. Following Tobin (1969), q is the ratio of the industries total value to the replacement cost of capital, $Pk \cdot K$, where Pk is the price of capital goods and K is the sectoral requirement for capital. Assuming quadratic adjustment costs, investment gradually moves sectors from their current to desired levels of capital stock. Unlike the myopic case, industries invest with knowledge of future capital prices – and all future prices and demands – so investment is determined by an intertemporal optimisation. A model with forward-looking behaviours gives rise to sectors' investment decisions which differ from the myopic case. Firstly, capital stock is shown to adjust in advance of demand disturbances, i.e. the shocks to demand produce anticipatory supply-side changes, and second, the sectors investing are aware that demand disturbances are temporary and so are not subject to "overinvestment" as arises in the myopic specification.

As noted in Allan et al. (2014a, p.126) the implications of the different investment behaviours for the timing of economic impacts are clear:

> "The outcome of these alternative capital specifications for temporary demand disturbances is that typically investment would occur quicker and earlier in the forward-looking case. Under myopia, however, it would be expected that sectors would 'overinvest' as sectors which experience the demand disturbance adjust their capital stocks without knowing that the demand disturbances will cease: their short-run desired capital stock will be greater than long-run equilibrium capital stock".

6.4 The contributions of papers three and four to the academic and policy literature

6.4.1 A more flexible way to model demand disturbances compared to IO and the identification of “legacy effects”

The first contribution of Papers Three and Four is an evaluation of the scale and timing of economic impacts from a set of temporary expenditures related to energy developments. There is an appreciation in the economic modelling literature that the dynamics of model results, i.e. the movement between one equilibrium and another, has been neglected (Partridge and Rickman, 2010). We begin this section by describing how IO models have captured the time dimension of demand shocks, and discuss how unsatisfactory this is, e.g. the need arbitrarily to ascribe specific “rounds” of the multiplier to time periods. Some applications of IO analysis have employed the “rounds” of the multiplier to decompose changes in economic activity over time periods, and we discuss this is Section 6.4.4. In Section 6.4.5 and 6.4.6 respectively we restate the features of the AMOS CGE model which give rise to observed “legacy” effects from temporary demand disturbances relating to marine energy developments.

6.4.2 Modelling demand disturbances in IO models

As described briefly in Section 3.2.3, “Fixed-price” analysis has previously been applied to demand shocks, and so we begin this section by discussing the treatment of time in “fixed-price” models.

6.4.3 Time in “fixed-price” models

In addition to the interpretation and scale of the multiplier, discussed briefly in Section 2.2.2, a further issue with multiplier analysis concerns the timing of impacts, that is the periods over which the multiplier effects occur.

For instance, a set of (exogenous) temporary demand shocks distributed over a number of years would be expected to have an impact that is also distributed over time. How these impacts could occur over time is an issue that is of interest to policy makers. A policymaker would be profoundly interested in, for example, the length of time between a change in government spending, for example, and a change in the level of economic activity.

Secondly, and in the case where a demand disturbance is permanent, an important question surrounds *when* the new equilibrium level of output will be reached. While such questions have clear policy interest, given the limited lives of governments, the literature on how IO models might address these is not well advanced. An early indication of the limitations of IO in this domain is provided by Mules (1983, p. 197), who writes that, “the traditional multiplier does not stipulate the time taken to realise effects, assuming instead that they usually occur immediately or within the space of one year”.

Miller and Blair (2009) devote only two pages to the time dimension of multiplier impacts. As they note Miller and Blair (2009, p. 653):

> “In the standard input-output model there is no consideration of the fact that production takes time; results are independent of time in the sense that f_{new} leads to X_{new} (via $X_{new} = Lf_{new}$). This is generally interpreted in something like the following fashion: “new demands, f_{new}, next period will lead to new outputs, X_{new}, next period.”

As noted earlier IO analysis assumes no capacity constraints. This means that any changes in demand feed instantaneously into changed levels of output. Hewings (1982, p.181) writes:

> “One of the more demanding assumptions embodied in the input-output framework is the absence of capacity limitations upon expansion in response

> to new demands placed upon industries."

Dorfman et al. (1958) describes how IO results exist in "artificial computational time", rather than "calendar time"[29]. Partridge and Rickman (2010, p. 5) note that "predicted outcomes [from IO models] are assumed to be realised immediately, which is unrealistic".

Mules (1983) argues that, by not including the time taken to realise effects, this:

> "deficiency in input-output methodology is a serious limitation, both in terms of intellectual acceptance and in terms of usefulness to policymakers for impact analysis".

Having said this, Rose (1995, p. 299) takes on the "misconception" that IO is a static model, arguing that this ignores the dynamic variant of the IO model specified in other writing of Leontief (e.g. see Miernyk (2004))[30].

The dynamic IO approach (Leontief, 1970) conventionally extended the IO analysis with a set of (sectoral) capital coefficients – measuring the holding of inputs from earlier periods which are not themselves used up in each period (the linkages between sectors describe the pattern of (flow) purchases required to produce output in that period – and (increased) demand for output can require the stock of capital to be changed for future periods). For a simple two-period case it is possible to determine a forward-looking variant, i.e. the (period 1) level of output given a set of (period 2) final demands and a need for capital adjustment between periods 1 and 2 – or a backward-looking expression, i.e. the (period 2) level of output given (period 1) levels

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[29] Dorfman et al. (1958, p.253-254) writes "Needless to say, the rounds of which we speak [The Gaitskiell multiplier chain] do not take place in calendar time, with the second round following the first... Artificial computational time is involved, and if we insist on giving a calendar time interpretation we must think of the Gaitskell process as going backward in time and the Confield process as showing how much production must be started many periods back if we are to meet the new consumption targets today".

[30] Leontief (1953, p.214) explains that a general dynamic solution of the IO system would allow a pragmatic question such as: "given the distribution of all available inventories and capacities at some initial point in time, at what particular constant rate can the final consumption of various commodities be maintained, say, during the next ten years, if at the end of the period the production had to reach such and such specified level?".

for final demands and outputs (Miller and Blair, 2009).

Specifically, we might rewrite the basic equation for the output of sector i in period t as:

$$X_i^t = \sum_{j=1}^{N} a_{ij} X_j^t + \sum_{j=1}^{N} b_{ij}(X_j^{t+1} - X_j^t) + F_i^t \tag{7}$$

where b_{ij} is the "capital-coefficient", representing the amount of output of sector i held as capital stock for production of one dollar's worth of ouput by sector j (Miller and Blair, 2009). Sector i is only able to expand therefore by increasing capital goods, including those produced by sector j.

We do not, however, use the dynamic IO system in the analysis employed in Papers Three and Four. This is for three main reasons. First, these models share many of assumptions of standard IO modelling, e.g. fixed technical coefficients in production, passive supply side, etc. Second, the dynamic systems further assumes that these (e.g. capital coefficients) are fixed through time. Third, these systems require knowledge of the level of sectoral capital required for each unit of production in all endogenous sectors. These data would not be collected as part of the set of IO or SAM accounts, and so would require to be estimated. This therefore appears to introduce increased subjectivity and complexity to the notion of dynamics, without any refinement in the nature of other key assumptions. We therefore develop and use a fully dynamic CGE model to explore the timing of economic impacts resulting from demand-side expenditures.

6.4.4 Rounds of the multiplier

The multiplier process can conceptually be decomposed into "rounds". The direct effect stimulates demand for the inputs to the directly stimulated sector in the first "round", then those sectors stimulated in the first round themselves stimulate demand for inputs from other sectors in the second round, and so on, through to round n:

$$\Delta X = \Delta f + L\Delta f + L^2\Delta f + L^3\Delta f + \ldots + L^n\Delta f \tag{8}$$

Miller and Blair (2009) identify formulae by which the (simple) IO method has been adapted to explicitly include a time dimension. In each case, these use the round-by-round process of conventional IO modelling, and equate impacts in each "round" to periods of calendar time.

For instance, Mules (1983) sets out how the round-by-round process continues in response to a specific shock in a sector, with the impact on any given round (R_n) being given as:

$$R_n = \sum_{t=1}^{t} G_{t-1} A R_{n-t} \tag{9}$$

where G_{t-1} is the lag operator for responses with a lag of $t-1$ periods, i.e. it captures the impact in round t of the new changes occurring in the previous $(t-1)$ period.

Mules (1983) allows for negative lags for some sectors which would be consistent with sectors anticipating the impact. By testing with different lags for sectors, Mules (1983) shows how much of the multiplier effect of a demand shock has been achieved after different rounds. While the timing of impacts is changed by assuming what are essentially arbitrary lags, the absolute size of the anticipated change given by the multiplier is unaffected: the approach allocates the multiplier effect through rounds which are interpreted as occurring through time.

The basic point made earlier however remains. To use a fixed-price system, e.g. IO or SAM, to explore the timing of economic impacts from a demand-side disturbance requires the imposition of essentially arbitrary assumptions, for instance, about sectoral production lags. Further, it requires the belief in absolute supply constraints – fixed, again, at an arbitrary level – and for these to have no impact upon prices. To consider the response of an economic system to demand-side disturbances, and the timing of that response, requires a system in which these assumptions can either be relaxed (e.g. with supply responding endogenously to economic conditions) or examined explicitly (e.g. the nature of firms or households' behaviours over the timing of investment or consumption being made explicit) within such models.

We now set out the processes through which "legacy effects" arise, beginning with the myopic case (Section 6.4.5) before turning to the forward-looking case (Section 6.4.6). The specific levels of the expenditures, and therefore the quantitative results, differ between Papers Three and Four, however in both – as described in Section 3.2.3 – the expenditures' time profile is broadly the same: increasing to a peak in the eleventh period. The time profile of the expenditures is consistent with the rate of installation required to achieve marine energy capacity targets in year 2020. This section briefly describes the timing of the results and the factors determining the existence of the observed "legacy" effects, that is, economic impacts which are caused by, but occur beyond the period of, a set of temporary demand-side disturbance. For details of the specific quantitative impacts on each variable of interest, the interested reader is directed to the content of these papers.

6.4.5 Legacy effects: The myopic case

If we begin with the myopic CGE case (explored in Paper Three and Paper Four), the principal explanation for "legacy effects" is the interaction between labour demand, wages, migration and regional competitiveness.

During the periods of the temporary expenditures, the demand for labour increases, putting upward pressure on the real wage and downward pressure on the unemployment rate, and encouraging in-migration to Scotland. Also, during the period of the temporary disturbances, the real and nominal wage rates increase, increasing household consumption in these periods.

While some sectors increase their output – as they are directly stimulated by the demand-side shock, or are connected to those sectors directly stimulated through backward linkages – there will be crowding out of activity in other sectors which, for instance, are labour intensive but do not see any increased demand for their products as, other things being equal, their costs have increased.

When the temporary expenditures cease, there is a sharp fall in real and nominal wages. These fall to below their base year values, which improves the competitiveness of Scottish output, acting as a further stimulus to the Scottish economy. Although wages and therefore consumption are now lower, the increase in competitiveness increases export demand which is sufficient to offset this in aggregate. As real wages are lower than their initial values (and the wage rate in rUK is assumed to remain constant at base year values in which there was an assumed migration equilibrium between Scotland and the rest of the UK) out-migration occurs, reducing labour supply and raising real wages until the initial base year equilibrium is re-established.

It is therefore the stimulus to economic activity resulting from migration and investment, serving as a boost to competitiveness, which causes the observed "legacy" effects. Allan et al. (2014a) show that the temporary disturbances in the myopic case give rise to an employment impact of 48,104 employment-years, with 28,648 (i.e. almost 60% of the total employment impact) occurring after the end of the temporary demand shocks[31].

6.4.6 Legacy effects: The forward-looking case

In addition to reporting the results from a standard demand-driven IO model and a backward-looking, or myopic, CGE model (as in Allan et al. (2008) and Gilmartin and Allan (2015)) Paper Four uses a CGE model (Lecca et al., 2013) with forward-

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[31] Almost 60% of the total GVA impact occurs as a "legacy" from the disturbance (Allan et al., 2014a).

looking behaviours for firms and households, described in Section 6.3.7. This paper demonstrates the importance of this assumption for the scale of economic impacts from a demand disturbance which is temporary and known to be temporary. As common sense would suggest, this resulting economic impact is quite different from the myopic case. Simply put, firms can adjust capital stock in advance of the demand disturbance through investment, and do not "overinvest" – as in the myopic case. Households do not linearly increase consumption in line with income increases, but can switch their spending away from the periods in which demand disturbances are made, in which the cost of consumption is more expensive. Further, the scale of the economic impact is compared against that which would be given from an IO analysis of the same demand disturbance.

In the forward-looking CGE case, firms and households plan investment and consumption in anticipation of changes in prices induced by the demand disturbance. With regards to consumption, unlike the increase in consumption during the periods of the temporary expenditures, observed in the myopic case, households reduce consumption during these periods as prices are higher, and increase their consumption relative to the base year levels in the periods following the end of the disturbance. With regards to investment, which is driven by changes in the real shadow price of capital, the same profile of temporary shocks drives an increase in capital stock *in advance* of the "peak" years of the disturbances, before falling sharply in those years, relative to the base level, and recovering to positive levels subsequent to the shock. The different profile of economic responses give rise to "legacy effects" on both GDP and employment under the forward-looking model which are around one-third of those found under a myopic model for the same temporary demand shocks (Allan et al., 2014a).

6.4.7 Why “legacy effects” matter for policy

This focus on the mechanism between expenditures and economic impact in a dynamic (i.e. period by period) CGE model reveals the pattern of these impacts across time, and the presence of “legacy effects”. We have defined these as economic impacts produced as a result of a set of demand-side disturbances, but which occur after the initial disturbances have ended.

The assessment of the size of “legacy” effects is critical for policy design and the evaluation of policy impacts. It shows that there are robust theoretical reasons for taking into account the period after any intervention for an economic consequence of that intervention. This would therefore caution against only looking for consequences during the period of intervention for a policy. For instance, we saw that for plausible model specifications about 60% of the employment impacts of a simple demand disturbance would occur in the periods after that disturbance ended. This is even in the absence of induced innovation or technological improvements in the delivery of the goods for the renewable energy development, and arises purely from the interaction of the expenditures and the supply side of the economy.

6.5 A new approach to explore the economic impacts of additional local content

Section 6.2 notes the significant expenditures associated with renewable energy developments and that there is considerable interest in the “local content” of those expenditures for driving economic development. A number of countries and regions have implemented local content requirements (LCRs) to mandate a minimum amount of expenditures associated with new capacity additions being made in the local/regional or national economy. This does not typically identify which category the expenditure relates to, but focuses on overall (i.e. global) costs. We saw earlier that there can be large variations in the extent to which different categories of costs might be sourced "locally" and that this depends upon the size of the local economy and the existence of technical expertise to deliver the components necessary.

Paper Three makes an empirical contribution to policy discussions on "local sourcing" of renewable energy expenditures. Specifically, this paper examines the additional employment effects on Scotland of fixed (absolute) percentage point changes in the extent of "local content" in each category for marine energy capacity. Our results inform the scale of the economic bonus for Scotland from additional "local sourcing" of expenditures on each component, and so could inform policy decisions about which expenditures would have the largest impact upon economic activity. As such, this paper makes a contribution to the discussion on the economic role of "local content requirements", which have been a feature of renewable energy development around the world (e.g. Kuntze and Moerenhout (2013)).

The economic impacts produced by additional local sourcing for each component takes account of both the scale of the expenditure under each component and the total impact for the Scottish economy of changes in that expenditure. This second point relates closely to the "multiplier" effect, and so these additional consequences from local sourcing could be considered as "local content multipliers". Paper Three demonstrates that the impact on regional employment of changes in local content differed significantly across components.

Local content can be derived from the amount of overall expenditures which are made in the local economy, e.g. through the purchasing of goods and services from the economic area, and can be summarised in terms of a percentage (%), for which a higher local content would have a higher percentage.

If β_j is a (percentage) measure of the local content for component j, for example, 1-β_j would be equal to the imported (non-local) content of the expenditures on that component. This is typically calculated for the initial construction phase of a project, which is often the largest outlay associated with renewable energy capacity.

Although this is a simple measure to calculate for existing projects (given available data) this is an area of significant academic (e.g. Kuntze and Moerenhout (2013)) and policy interest. In Scotland, for example, interest in the local content for renewable energy technologies is manifest through the National Renewables Infrastructure Plan (e.g. Scottish Enterprise and Highlands and Islands Enterprise (2010) and Scottish Enterprise and Highlands and Islands Enterprise (2012)). Building narratives for UK offshore wind scenarios, it has been noted that UK content in offshore wind capacity could increase as offshore wind capacity increases, and this might produce economic benefits for the UK economy (Offshore Renewable Energy Catapult, 2014).

For renewable energy technologies, the local content can be small, but can vary considerably for different technologies and for categories of expenditures. For the expenditures related to a recent offshore wind project in the UK, it has been estimated that the share of total capital expenditures which would be spent in the UK would be around thirty-two per cent, although this varies between different elements of these expenditures (Roberts, 2011).

Paper Three considers the impacts of changes to local content from a “bottom-up” estimation of technology costs; the pattern across expenditure categories; and an assumed Scottish share of expenditure in each category.

The key table from the paper (Table 3 in Gilmartin and Allan (2015)) is reproduced in Table 7. The first column shows the different expenditure categories involved in the development, construction and installation of marine energy devices. The second shows the importance of each category to total expenditures in each year. For instance, almost 50% of all annual expenditures were between the “Structure” and “Mechanical plant” categories. The allocations of total expenditure to categories was taken from Sgurr

Energy and IPA (2009). The final column shows the values for b_j for each expenditure category j, i.e. the percentage share of expenditure in each category which is assumed to be spend in Scotland.

Table 7: Categories of expenditure, share of annual expenditure that falls in each category, share of expenditure by location

Category	Share of annual expenditure in this category (%)	Scottish (i.e. local) content
Conceptual engineering	0.33	50.0
Expert resource	0.28	45.0
Site/resource assessment	0.80	58.3
Detailed engineering	0.77	43.8
Component testing	0.73	40.0
System integration testing	0.70	56.7
Verification third-party approvals	0.45	25.0
Structure	34.37	69.6
Mechanical plant	14.37	11.0
Electrical plant	5.73	29.2
Control and monitoring systems	1.13	43.4
Cables, umbilicals and communications, grid connection	5.30	31.4
Moorings and foundations	9.18	51.2
Onshore equipment	0.93	46.7
Other	4.66	86.7
Logistics base (e.g. ports/harbours)	1.07	97.5
Installation vessels	6.66	36.7
Support vessels	4.93	55.0
Diving	1.60	83.3
Survey	0.87	82.5
Onshore civil engineering	1.40	90.0
Testing and pre-commissioning	1.20	70.0
Project management	2.53	77.5

The Scottish content of each category of expenditures was also taken from Sgurr Energy and IPA (2009). It can be seen from Table 7 that these differ across categories, ranging from 11.0% for "Mechanical plant" to 97.5% for "Logistics base". Overall, we estimate that 52.7% of total costs are sourced in Scotland in aggregate[32]. Each expenditure category was allocated to one of eight sectors in the model, while the other seventeen sectors did not directly receive a demand stimulus, but are affected through linkages to the sectors receiving these disturbances and through the consequential changes in input (intermediate and factor) prices which could affect the competitiveness of their output.

It would be interesting to examine the factors which explain a high local content for these items, but our focus is on the impact of additional local content so we do not examine it further. It is likely that, *ceteris paribus* the local content will be higher for categories which have relatively higher costs of transportation (e.g. the share of "Onshore civil engineering" element could be high as the cost of transporting structural elements makes it likely that these would be sourced in Scotland) or which have a need to use local services due to existing knowledge in the local area (e.g. the high local content for "Diving" and "Logistics base" could reflect existing local technical skills).

The assessment of the impact of increasing the share of local content takes a straightforward approach. As the paper notes, the local sourcing of each category was increased by one percentage point, i.e. the Scottish content of total expenditure on the "Cables category, etc." from 31.4% to 32.4%, giving a higher amount of overall expenditure, and thus demand disturbance, to be introduced to the model, and which the higher expenditure was in the "Insulated wire and cables" sector of the model (sector four). The simulations were run an additional 23 times, with each simulation sequentially

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[32] Paper Three describes that "it is assumed that the regional sourcing for each cost category remains constant across the years of the simulations...[and that this ignores] the possibility that increase development of marine energy capacity capacity in Scotland could lead to a local supply chain in which a greater share of spending might be sourced in Scotland" (Gilmartin and Allan, 2015, p.343).

increasing the extent of Scottish-sourcing of each category by one percentage point, giving a higher level of expenditure in a specific sector over the assumed time path of the expenditures. We are especially interested in the additional job impacts of alternative local content assumptions, and so we report the present value of employment (in person years) for each category of expenditure that is additional to the original simulation. Note that these changes in employment occur across all sectors, including the directly stimulated sector in which the higher local content means a greater stimulus to demand.

Figure 2[33] shows the additional employment (in person years of employment, as a present value) for an additional 1 percentage point sourced in each category against the 'base case' assumptions on local content.

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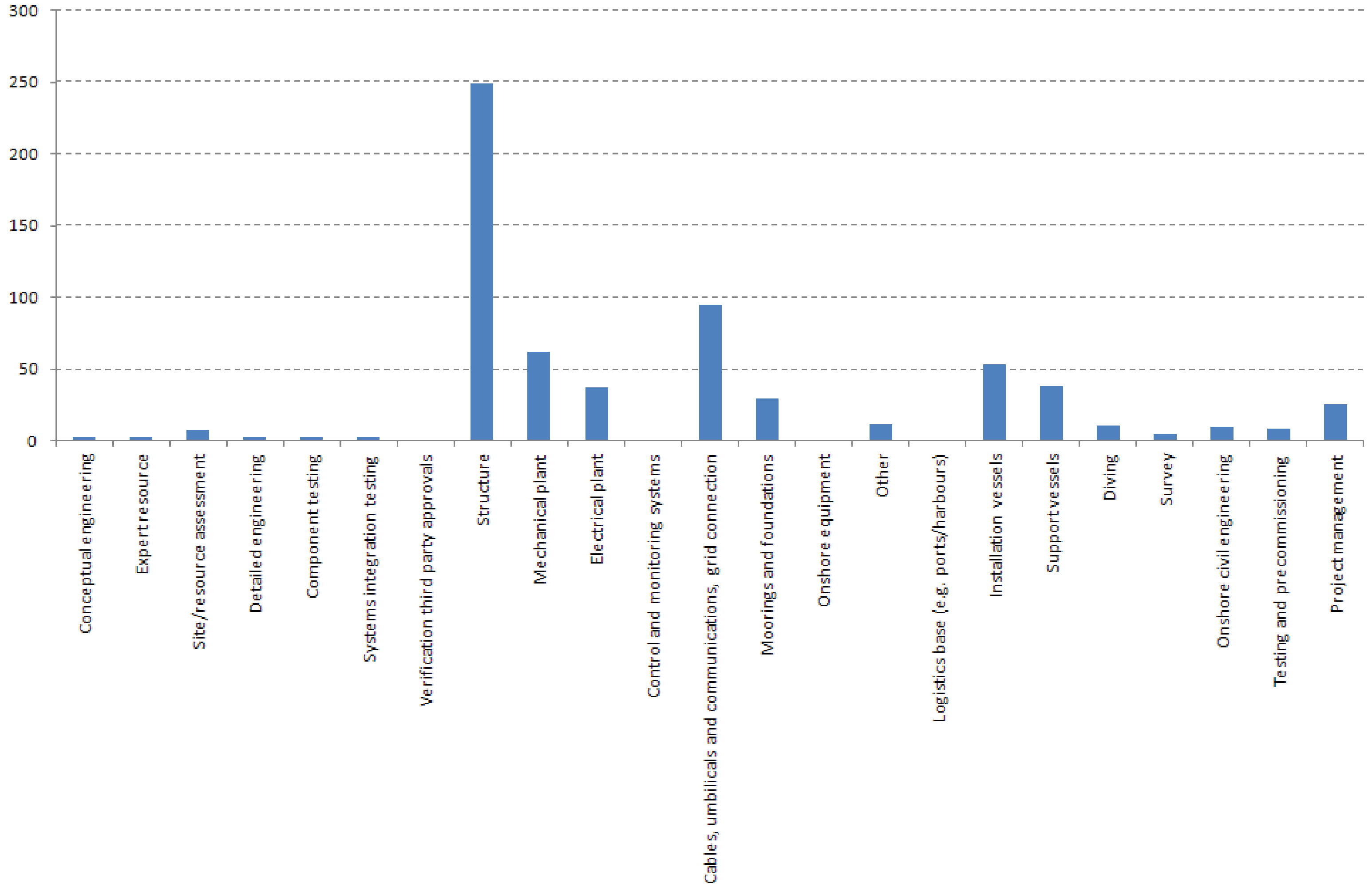
[33] This is Figure 10 in Gilmartin and Allan (2015).

Figure 2: Additional employment for an additional one percentage point of expenditure in each category in Scotland sourced in Scotland; absolute differences from ’base case’ scenario



These results show the importance of modelling the system-wide consequences of local content changes. As we would expect, given that the "Structure" category has over one-third of all expenditures in each year, increasing the local content in this category has a large additional impact on employment. Raising the local content by 1 percentage point adds an additional 249 person years of employment in present value terms. At the opposite end of the scale, the "Onshore equipment" component has only 0.93% of expenditures in each year and increasing the Scottish share of its expenditures (in Sector 5) has approximately zero impact on employment over the simulation.

As interesting as these insights are for the quantitative impacts of additional local sourcing, there is an important further result from Figure 2, which demonstrates a powerful lesson from the system-wide modelling. If it was only the scale of expenditures which was important, we would expect the pattern in additional employment to reflect this. However, it is clear that the second largest employment effect is for the expenditure category "Cables, etc." with an additional 95 person years of employment (in present values) for an additional one percentage point of local sourcing. This category only has 5.3% of costs in each year, which is similar to the "Electrical plant" category and "Support vessels" with 5.73% and 4.93% respectively. Both of these categories see an additional employment effect that is less than two-thirds of that for "Cables, etc.".

The underlying explanation of the additional employment stimulated by increases in the local content of this expenditure category is that these expenditures are introduced to sector five – the "Insulated wire and cables" sector. This sector has the largest (aggregate) employment effect per expenditure of all eight of the directly stimulated sectors (Figure 9 in Gilmartin and Allan (2015)) with each £1million of expenditure increasing employment by over 70 person years of employment. This was almost three times the employment impact of all expenditures taken together (24). Additional local sourcing in the "Insulated wire and cables" category increases expenditure in the sector which has the largest employment impact per unit of expenditure. This explains the high additional employment of a category which otherwise has a relatively small share in all expenditures, and suggests that focusing on increasing the share of global expenditures sourced in the "local" area should also take into account the system-wide knock-on consequences of these expenditures.

7 CGE modelling of energy efficiency improvements

In Chapter 6 we used a CGE model of Scotland to examine the system-wide consequences of a set of (temporary) demand-side disturbances, and compared the results from this to those from an IO system. In this Chapter, and in Chapter 8, we present two papers which use the (adapted) AMOS CGE modelling framework to analyse policies which have their principle impact on the supply-side of the economy. This Chapter describes the contribution of Paper Five, briefly introduced earlier in Section 3.2.4, which explores the economic and energy consequences of improvements in the efficiency of energy use in industries (Allan et al., 2007c).

Improvements in energy efficiency have been proposed as one major solution to reconciling the apparent conflict between growing economic activity and reducing the impact of that activity on the environment. With energy efficiency defined as the amount of output produced per unit of energy, improving energy efficiency suggests that improving the amount of output that can be produced by a unit of energy, there will be less energy use, and thus lower emissions.

We will see however, that the consequences of improving energy efficiency can differ from what is intended by policy. It transpires that such policies could have an ambigious impact on the consumption of energy, rather than (necessarily) reducing energy use. Further, these impacts arise from interactions within the economy that a CGE model is particularly suited to examine.

The terms "rebound" and "backfire" concern the outturn consequences for energy demand following an improvement in energy efficiency. "Rebound" refers to the cases where energy use falls by less than the improvement in energy efficiency. "Backfire" refers to when the use of energy actually increases following a stimulus to energy efficiency. At the same time, we will also see that – alongside the consequences for energy use – improvements in energy efficiency typically produce economic consequences.

This Chapter proceeds as follows. Section 7.1 describes the motivations for energy efficiency policies, and specifically describes policies in the UK and Scotland. This also introduces the notion that improvements in energy efficiency may give rise to other consequences, which may not be considered in the motivation for the policy. Section 7.2 introduces the concept of rebound and its definition. Section 7.3 describes the particular usefulness of CGE modelling to the analysis of energy efficiency, while Section 7.4 describes paper five (Allan et al., 2007c), including the model structure, database and simulation strategy[34].

The specific contributions of paper five to the academic and policy literature are highlighted in Section 7.5. These include being the first empirical assessment of the scale of "rebound" for the UK economy. Second, this paper demonstrates the sensitivity of the modelled results to the assumptions of the model, and identifies a useful direction for future research.

7.1 Energy efficiency policy and its possible consequences

There has been considerable policy interest in promoting energy efficiency improvements, principally dating from the mid-1990s as policy makers sought policies which might both reduce emissions and break the link between economic activity and the use of resources, including energy. A leading and ambitious book in the popularising of the concept of "resource productivity" was Factor Four (Von Weizsäcker et al., 1998) which sought to demonstrate that improving the productivity of natural resources ("by a factor of four") was technically possible and would simultaneously reduce the demands that the economy places on the environment, and improve economic outcomes

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[34] To be clear, the first use of the AMOS model framework to energy efficiency was an application to Scotland published in Renewable Energy in 2006 (Hanley et al., 2006). Between January and May 2006, the PhD candidate (with co-authors both in the Fraser of Allander Institute and at Stirling University) worked on a report for DEFRA modelling the consequences of improvements in energy efficiency for the UK as a whole, the report on which was published in May 2006 (Allan et al., 2006). That report formed the basis for the work reported in paper six (Allan et al., 2007c).

for the planet[35]. One of the first UK policy documents in this area took the idea of energy efficiency as “a key to change” in achieving sustainable development, and that economic and environmental objectives can be met “at the same time” (Performance and Unit, 2001).

Current UK policy on energy efficiency dates from the recent “Energy efficiency strategy” (Department of Energy and Climate Change, 2012). This set out the UK Government’s aspiration for energy efficiency, noting that:

> “Through greater energy efficiency we can use less primary fuel or power to enjoy the same level of output. For example, by improving manufacturing equipment it is possible to produce the same or more with lower overheads. Improved energy efficiency can provide many economic, social and environmental benefits for the UK and yet we are not doing all we can to realise them” (Department of Energy and Climate Change, 2012, p.7).

The report notes the benefits for economic growth of improving energy efficiency are noted, and additional impacts in reducing emissions and improving energy security. With regards to the economic consequences, these are described both in terms of short-term jobs, “installing energy efficiency measures”, and long-term gains through reduced running costs for firms, and increases in productivity. The report notes “simple changes in energy use behaviour can deliver some of these benefits with little up-front cost”. The strategy also notes that improved energy efficiency can reduce energy use and bills for households. Interestingly, the report notes the potential for direct and indirect “rebound” for households, following improvements in energy efficiency, but does not acknowledge the notion of “economy-wide” rebound. We will return to these terms in Section 7.2.

More recently, (Parsons Brinckerhoff and DNV GL, 2015, p.1) produced a report for

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[35] Von Weizsäcker et al. (1998, p. xviii) define resource productivity as “the amount of wealth extracted from one unit of natural resources” and suggest that this could quadruple: “thus we can live twice as well – yet use half as much”.

the Department of Energy and Climate Change on the "potential for and challenges of realising carbon dioxide emissions reductions across [eight] sectors" of the UK economy. The sectors studied are all industrial (i.e. production) sectors, and were selected due to being highly energy-intensive, producing two-thirds of industrial emissions in the UK[36]. This recent report suggests both continued key policy interest in energy efficiency in the UK, and an awareness that the consequences of energy efficiency improvements in different sectors could be quite distinct.

The UK energy efficiency strategy notes that energy efficiency policy in the UK "needs to take into account" differences between the devolved regions of the UK. In Scotland and Wales, "encouragement" of energy efficiency is a devolved responsibility – under the control of the parliament in Edinburgh and Cardiff respectively, while "regulation" of energy efficiency in both regions is reserved to the Westminster parliament, and the UK government. In Northern Ireland, the encouragement and regulatory responsibilities around energy efficiency are devolved.

Energy efficiency has remained a central plank of the Scottish Government energy policy. In the foreword to the Scottish Government's 2010 "Energy efficiency action plan for Scotland", the then First Minister, Alec Salmond, wrote:

> "[The Action Plan] reaffirms our ambitious energy efficiency... agenda for Scotland. It sets out our wide-ranging programme of activity on behaviour change, household, business and public sector energy efficiency... and it is a key component of our broader approach to meeting Scotland's climate change targets and securing the transition to a low carbon economy in Scotland... By maximising the output from our energy inputs, energy efficiency and productivity offer a way to curb energy consumption without limiting growth and hence to reduce emissions whilst still growing our economy" (Scottish Government, 2010, p. 1).

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[36] Specifically, the eight sectors are Cement, Chemicals, Food and drink, Glass, Iron and steel, Oil refining, and Pulp and paper".

The same report notes the apparently straightforward consequences of improving energy efficiency: "energy efficiency seeks to maximise the output from a given set of energy inputs and thereby to improve energy productivity and reduce overall energy consumption" (Scottish Government, 2010, p.11). Further, it also sees other benefits of improvements in energy efficiency:

> "It offers a platform to limit or reduce emissions that does not necessarily limit economic growth as it seeks to reduce costs for businesses and homeowners, boost productivity, and provide some in industry with new markets. We want to make our energy supply itself more efficient, whilst additionally boosting our energy security. Our work in energy efficiency will support wider resource efficiency, play its part in creating more highly skilled and better paid jobs, and help to build our competitiveness in a new international market." (Scottish Government, 2010, p.11).

Additionally, in June 2015, the Scottish Government's "Heat Policy Statement" set out that energy efficiency – with a particular focus on households – was to be designated a "National Infrastructure Priority", whilst energy efficiency is also an "investment sector" for the Green Investment Bank, launched in 2012.

However, these statements about there being a clear link between improving energy efficiency and reducing energy use, omits an important economic dimension, which was first raised by Jevons (1865) and which has been resurrected in the recent economic literature by, most notably, Khazzoom (1980); Brookes (1990); Saunders (1992). That is, that improvements in the productivity of a factor of production, such as energy, does not necessarily mean that less of that input is used. In some cases, this argument continues, there could be an increase in the use of the input which has seen the efficiency of its use improved. Before looking at the most recent academic work – to which Paper Five contributes – it is useful to describe the precise channels through which Jevons' original argument proceeds.

Jevons was principally concerned with tackling the argument for increased efficiency in the use of coal due to its increasing use in steam engines, with the fear that UK coal resources would be exhausted rapidly. The conventional wisdom therefore encouraged users of coal to become more efficient in their use of that input, i.e. produce more output for the same volume of coal, or produce the same amount of output using less coal. By doing so, it was argued, less coal would be used, and that the UK's coal reserves would not be depleted too quickly: (Alcott, 2005, p.12) writes of the conventional thinking of the time as encouraging "the efficient use or 'economy' of fuel as a chance to 'save' it and postpone the day of reckoning" [by which the resource would be exhausted].

That line of reasoning was, however, comprehensively refuted by Jevons, with Alcott (2005) arguing that Jevons' argument is "unequivocally for backfire". His idea developed from observing that increases in the usefulness of coal-power steam engines would lower the cost of production in the iron industry, further encouraging production using lower cost coal, stimulating additional demand for activities using both steam and coal and so greater coal use (Sorrell, 2009). He wrote that "it is the very economy of its use which leads to its extensive consumption" (Jevons, 1865, p. 141).

Writing in more recent times, Sorrell (2009) describes how Jevons' example from the iron industry gives plausible consequences for the development of modern more energy efficient technology, which has potentially multiple applications across uses of a resource, radically transforming the use of resources[37]. Sorrell writes that perhaps more mature production processes may not see such extreme impacts from improvements in efficiency in the use of energy.

More generally, the modern "rebound" debate is critical for this paper. While different terminologies are used – and will be discussed in Section 7.2 – this is the empirical, and

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[37] Sorrell (2009) also gives the similar example of the Bessemer steel-making process, described in Rosenberg (1989), as rapidly lowering the cost of the production of steel rails, enabling the rapid growth of the rail industry and making it possible to "employ steel in a wide variety of uses that were not feasible before Bessemer, bringing with it large increases in demand. As a result, although the process sharply reduced fuel requirements per unit of output, its ultimate effect was to increase the demand for fuel" (Rosenberg, 1989).

in theory testable, notion that, following an improvement in energy efficiency, there may not be a comparable reduction the amount of energy used.

7.2 Definitions of "rebound"

The notion of rebound from energy efficiency improvement has been widely studied in the academic literature. However, several definitions exist, with each capturing a particular aspect of the measurement of the impact of improvements in energy efficiency on the use of energy (i.e. the potential or measured energy savings). As Sorrell (2009, p.1457) notes, the transmission link between improvements in energy efficiency and use of energy is a straightforward economic optimisation question:

> On the micro side, the question is whether improvements in the technical efficiency of energy use can be expected to reduce energy consumption by the amount predicted by simple engineering calculations. Simple economic theory suggests that it will not. Since energy-efficiency improvements reduce the marginal cost of energy services, such as travel, the consumption of those services may be expected to increase. This increased consumption of energy services may be expected to offset some or all of the predicted reduction in energy consumption.

In this short section, we describe three definitions of rebound, which are respectively, the *direct*, *indirect* and *economy-wide* rebound effect. These definitions are important as they have implications for the the most useful model that can be used to identify the scale of these.

We do not systematically review the estimated scale of each measure of "rebound", however Gillingham et al. (2015) provides some estimates of the first two measures of the rebound effects, while a relatively recent review of the scale of system-wide estimates of the rebound effects using CGE models is provided in Allan et al. (2007b).

7.2.1 Direct rebound

Sorrell (2009) writes that the notion of direct rebound in the energy economics literature began with the work of Khazzoom (1980). This was the notion that an improvement in energy efficiency would lower the price of the energy service provided by that good, and so encourage greater use of the energy service. In the absence of rebound, consumption of the energy service would fall in line with the improvement in energy efficiency. In the presence of rebound however, there would be a less than equivalent fall as a portion of the potential energy savings are not realised (early studies referred to the "take-back" of the potential energy saving). Gillingham et al. (2015, p.6) write that "the 'direct rebound effect' is generally defined as the change in energy use resulting from the combined substitution and income effects on the demand for energy-efficient product". That paper also notes that the elasticity of demand for an energy service is typically calculated with regards to its own price, and so provides a measure of the extent of direct rebound.

One example of a well studied area of direct rebound research concerns the improvements in fuel efficiency in motor vehicles, and the changes in energy demand that result from this. Gillingham et al. (2015, p.7) write that empirical studies of this topic typically define the fuel price elasticity of demand as the direct rebound effect. The literature suggests price elasticity of demand for gasoline or driving lie "generally in the range of -0.05 to -0.4... suggest[ing] a direct rebound effect of the order of 5 to 40% (*ibid*, p. 9).

7.2.2 Indirect rebound

Whether or not direct rebound is observed, an improvement in energy efficiency may lead to increases in demand for energy services through effectively increasing real incomes. These are typically termed the “indirect” rebound effect [38]. For instance, a driver of a more fuel efficient car will subsequently have income remaining after motor costs, and could spend this income on goods which themselves require the use of energy.

Gillingham et al. (2015) notes that there are a number of studies of indirect rebound, mainly from developed countries. Some of these use Input-Output tables to consider the economic and environmental impact of respending of incomes, while others estimate income elasticities e.g. Druckman et al. (2011). That paper suggests that the extent of indirect rebound critically depends on the use of “avoided expenditures”, i.e. those savings from household budgets coming from improvements in energy efficiency. In their “best” case for rebound, the lowest (indirect) rebound effect they find is 12%, when savings are spent on additional housing activities – the expenditure category with the lowest greenhouse gas intensity.

7.2.3 Economy-wide effects

Greening et al. (2000) notes that preceding definitions of rebound capture only direct or secondary responses to improvements in energy efficiency. This omits the consequences for “price and quantity readjustments or economy-wide effects” further stimulated by these changes. The overall change in energy consumption following a change in energy efficiency cannot simply be found from summing the direct and indirect effects[39]. Greening et al. (2000, p.391) argues that the economy-wide impacts for consumption and investment could be significant, given that changes in energy efficiency could have a major impact on the “composite price of energy services” . Writing in 2000, they

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[38] Gillingham et al. (2015) writes that “it is most common to refer to the indirect rebound effect as only the income effects on the consumption of all other goods”; Sorrell (2009) alternatively describes these as “re-spending effects”, and also describes “embodied energy effects”, where the specific item serving to improve energy efficiency, such as the more fuel efficient engine, embodies an amount of energy required for its manufacturing.

[39] Gillingham et al. (2013) points out that one cannot sum the direct and indirect effects to get the overall impact as “any direct rebound decreases the amount of money to spend elsewhere”.

note that “the size of rebound from this source is highly uncertain and deserves further study”. In the next section, we describe why CGE models are particularly suited to examining the economy-wide rebound effect.

7.3 The value of CGE analysis

Greening et al. (2000, p.397) is clear on the benefits of a general equilibrium approach to understanding the consequences of improvements in enegry efficiency, writing:

> “Because improvements in energy efficiency, with resulting increases in the supply of energy services, alter the mix of both final and input demands, increase consumers real income, and expand firms production possibilities, prices throughout the economy will undergo numerous, and complex adjustments. Only a general equilibrium analysis can predict the ultimate result of these changes.”

We can be more specific. Allan et al. (2007c) notes the critical distinction between energy in natural units, E, and energy in efficiency units, ϵ. With an improvement in energy efficiency, ρ, energy in efficiency units can be expressed as:

$$\epsilon = (1+\rho)E \tag{10}$$

The price of energy in efficiency units, P_ϵ, is obtained from the price of energy in natural units and the effiicency of each (natural) unit:

$$P_\epsilon = \frac{P_E}{1+\rho} \tag{11}$$

where P_E is the price of energy in natural units. With a positive ρ – i.e. a positive improvement in energy efficiency – it can be seen that price of energy in efficiency units will fall (i.e. P_E is less than $P_E/(1+\rho)$).

As is noted in Paper Five, whether the improvement in energy efficiency leads to an increase or a decrease in energy use for the economy as a whole "depends solely on the general equilibrium own-price elasticity of demand for energy" in efficiency units (Allan et al., 2007c, p.782). This is the relationship between the quantity of energy demand and the price of energy, in a general equilibrium system in which all other prices, demands, outputs, and factors of production are able to adjust to a new equilibrium. (This contrasts to a partial equilibrium system, for example, in which only one market is examined.) With a general equilibrium own-price elasticity of demand for energy of less (greater) than one, for example, there would be a fall (rise) in energy demand following the improvement in energy efficiency.

Allan et al. (2007c) notes that there are three effects working to increase the use of energy following an improvement in the efficiency of energy use in production: specifically, substitution, income and output effects. These are respectively, that a lower price of energy in efficiency units, 1) encourages firms to move towards more energy intensive forms of production; 2) permits households to spend additional real incomes on (now cheaper) activities, and; 3) by lowering prices, this increases the competitiveness of goods, stimulates demand, output and energy use[40]. However, the general equilibrium own-price elasticity of demand for energy will not be readily available to estimate for an economy. For instance, in a general equilibrium system the price of energy in efficiency units will be endogenous, making it critical that the assessment of the extent of rebound be estimated using such a model.

An additional benefit of a CGE approach to considering the scale of the economy-wide rebound effect is that such models should usefully reflect the nature of economic relationships of the economy in question. This is critical as the degree of rebound for an economy cannot be read across from other studies. The paper notes that "the extent of rebound and backfire effects is always and everywhere an empirical phenomenon". For

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[40] This could lead to a change in the structure of output, since there will be larger falls in the relative price of output for those sector(s) for whom energy is a more important input to production.

instance, (Allan et al., 2007c, p.783) notes that there are a huge number of parameters and details on the nature of production, consumption and openness of the economy in question:

> "...within a general equilibrium context, characteristics such as the openness of the economy, the elasticity of supply of other inputs (capital and labour), the energy intensity of individual production sectors and final demands, the elasticity of substitution between commodities in consumption and the income elasticity of demand for commodities are particularly important."

This long list suggests that the appropriate use of CGE models in this context necessitates a detailed sensitivity analysis of the importance to such key variables, and this is one of the contributions of Paper Five (discussed later in Section 7.5.3).

7.4 Modelling energy efficiency

Earlier in this chapter, we discussed the environmental case for improving energy efficiency and the benefits of using a CGE model to explore the consequences. As noted earlier, these could include inducing firms to substitute towards the use of greater use of efficiency units of energy in production, which might cause there to be a smaller fall in energy use than might be expected. We saw earlier that where energy use falls by less than the improvement in energy efficiency, this is termed "rebound", while if the amount of energy used actually increases as a consequence of improving energy efficiency, this is referred to as "backfire".

We now turn to examine the application of Paper Five (Allan et al., 2007c), which applied the UKENVI model – a CGE model calibrated on UK data – to explore the system-wide effects of improvements in the efficiency of energy use in production. The paper considered an improvement in efficiency in energy use "across the board", i.e. in all UK production sectors.

Section 7.4.1 sets out the UKENVI model, beginning with the structure of production in this model before exploring the database on which this model is based, and the parameterisation of production, trade and other key relationships (Section 7.4.2). Section 7.4.3 describes the simulation strategy employed, and the assumptions made in the simulation which is presented in the central scenario of the paper, and then sensitivity scenarios.

7.4.1 Production structure

UKENVI uses the same CGE modelling framework of AMOS, so there are many similarities – as well as a number of major differences – between the approach and specification of the model structure described in Section 6.3. This section details the differences in the two models, and the rationale for these. There are three transactor groups - households, corporations and government, and one external transactor (the rest of the world). There are four components of final demand, which are household consumption, government, exports and investment. As in Paper Three, we use the backward-looking form of the AMOS framework, in which each sector updates its capital stock between periods using investment flows net of depreciation during the period. Sectoral investment in capital stock is driven by rate of return to capital relative to the user cost of capital. Gross investment in each period is sufficient to cover depreciation of last period's capital stock and a portion of the gap between current and desired capital stock.

In contrast to the models used in Papers Three and Four – where we were particularly concerned with the timing of economic impacts from temporary demand disturbances – in this application we do not examine the dynamics of adjustment following the economic change. We are however interested in understanding the consequences of improvements in energy efficiency and the scale of rebound in two alternative conceptual time periods, the "short-" and "long"-runs. Each is defined as follows: the short run is the period in which the capital stock is fixed at its initial level, while population is fixed in aggregate (i.e. total labour force is fixed, however the labour supply increases with the real wage rate) while labour is able to move between sectors. We discuss the specification of the labour market shortly.

In the long-run, it is assumed that all sectors fully adjust their labour and capital stocks to their new equilibrium values, so that actual capital stocks are equal to desired capital stocks in each sector – i.e. all investment necessary to adjust capital stocks to the level desired given sectoral value added, the user cost of capital and the wage rate, have taken place. There is also equilibrium in the labour market, again characterised by a fixed total population but a positive relationship between labour supply and the real wage rate in the central scenario.

Turning to the specification of the labour market, there is one crucial difference between the treatment compared to the applications in Section 6.3. Unlike Paper Three and Four which had a regional (Scotland) focus, in this application we run the model with fixed population, i.e. no migration is permitted. This is a useful simplification, and reasonable to represent the labour supply for a national economy, such as the UK; the contention being that there are constraints on the ability of labour to move between nations, which do not exist to anything like the same degree for labour moving between regions of a national economy (i.e. between Scotland and the rest of the UK).

We assume a single UK-wide labour market, in which workers are costlessly able to move between employment in different industrial sectors. Further we assume in the central scenario that workers wages are governed via a real wage bargaining process, in which workers bargaining power is inversely correlated with the unemployment rate (e.g. Layard et al. (1991)). The bargaining function takes the following form:

$$w_t = \alpha - 0.068u + 0.40w_{t-1} \tag{12}$$

where w is the real consumption wage for the UK, u is the unemployment rate, t is the time parameter, and α is a parameter calibrated to ensure that there is equilibrium in the initial base period.

However, this specification of the UK labour market clearly matters for the model simulations. As a result, it is sensible to consider alternative specifications, and in Paper Five we consider two limiting special cases of possible wage setting processes in the UK labour market. The first of these assumes that labour supply is exogenous, suggesting a perfectly inelastic labour supply curve at the initial level of employment. There would thus be no changes to the level of employment for any given change in the demand for labour, however the wage rate would change accordingly to ensure equilibrium in the labour market at the initial level of employment. This is clearly a limiting case, but it is noted in the paper that this is a common feature of national CGE models.

A second limiting case of the labour market assumes a labour market in which real wages are fixed (as in real wage resistance models), and that therefore employment would adjust fully to a given change in the demand for labour (i.e. that labour supply is, contrary to the first specification, in effect, infinitely elastic at the initial wage rate. In the central scenario the labour market is characterised by a real wage bargaining specification, in which real wages and employment adjust to changes in labour demand, so that this is therefore a case that is intermediate to the two limiting alternative specifications. As we will see, when we look at the results across all sensitivity analysis performed, the specification of the labour market is important, and thus warrants this careful attention.

The UKENVI model has 25 commodities/activities, which are given in Table 8. There are five energy sectors, which correspond to the production and sales of four energy commodities (coal, oil, gas and electricity, of which we separately identify renewable and non-renewable electricity generation). More details on the sectors identified – including how the disaggregation of the electricity sector by generation type was obtained – is given in Section 7.4.2.

Table 8: Sectoral aggregation for Paper Five

Sector	Sector name	SIC(92)
1	Agriculture, forestry and fishing	1,2,5
2	Other mining and quarrying, including oil and gas extraction	11 to 14
3	Food and drink	15.1 to 16
4	Textiles	17.1 to 19.3
5	Pulp, paper and articles of paper and board	21.1 to 21.2
6	Glass and glass products, ceramic goods and clay products	26.1 to 26.4
7	Cement, lime plaster and articles in concrete, plaster and cement and other non-metallic products	26.5 to 26.8
8	Iron, steel first processing	27.1 to 27.5
9	Other metal products	28.1 to 28.7
10	Other machinery	29.1 to 29.7
11	Electrical and electronics	30 to 33
12	Other manufacturing	20, 22, 24.11 to 25.2, 34 to 37
13	Water	41
14	Construction	45
15	Distribution and transport	50 to 63
16	Communications, finance and business	64.1 to 72, 74.11 to 74.8
17	Research and development	73
18	Public administration and education	75, 80
19	Health and social work	85.1 to 85.3
20	Other services	90 to 95
21	Coal extraction	10
22	Oil processing and nuclear refining	23
23	Gas	40.2 to 40.3
24	Electricity – renewable	part of 40.1
25	Electricity – non-renewable	part of 40.1

As with AMOS, described above, a key feature of the modelling framework is the use of multi-level production functions, in which we impose cost minimisation in production. The specific multi-level production structure is shown in Figure 3, while the differences in production structure from papers three and four can be seen by comparing Figure 1.

As in these earlier CGE papers, the production function takes the same form for all sectors[41]. Substitution at each level of the production structure is assumed to be of Constant Elasticities of Substitution (CES) form. This means that sectors substitute between inputs in production in response to changes in their relative prices. Due to the presence of zeros in the initial database for the model, we impose Leontief technology (i.e. zero substitution) in all sectors in two places; within the non-energy composite, and between coal and gas in the non-oil composite.

Unlike Papers Three and Four, there is a more detailed disaggregation of energy commodities/activities in the version of the modelling framework used in this application. This specification of energy within the production structure is another important decision to be taken during model construction, as this can have important consequences for the modelled results. The principle of where energy should enter the production function is a keenly contested area of research, as this determines the substitutability of energy with other inputs. At the point of the writing of paper five, this was an area where there was "currently no consensus" (Allan et al., 2007c, p.785). The paper notes that in CGE models energy would most typically substitute with capital (e.g. Bergman (1988, 1991)), but that energy has also been introduced with other intermediates (e.g. Beauséjour et al. (1995)).

The principle of where the most appropriate treatment of energy inputs, i.e. where energy "should" feature in CGE models) was most recently analysed by Lecca et al. (2011). Their paper notes that there is a variety of treatments of energy in CGE models

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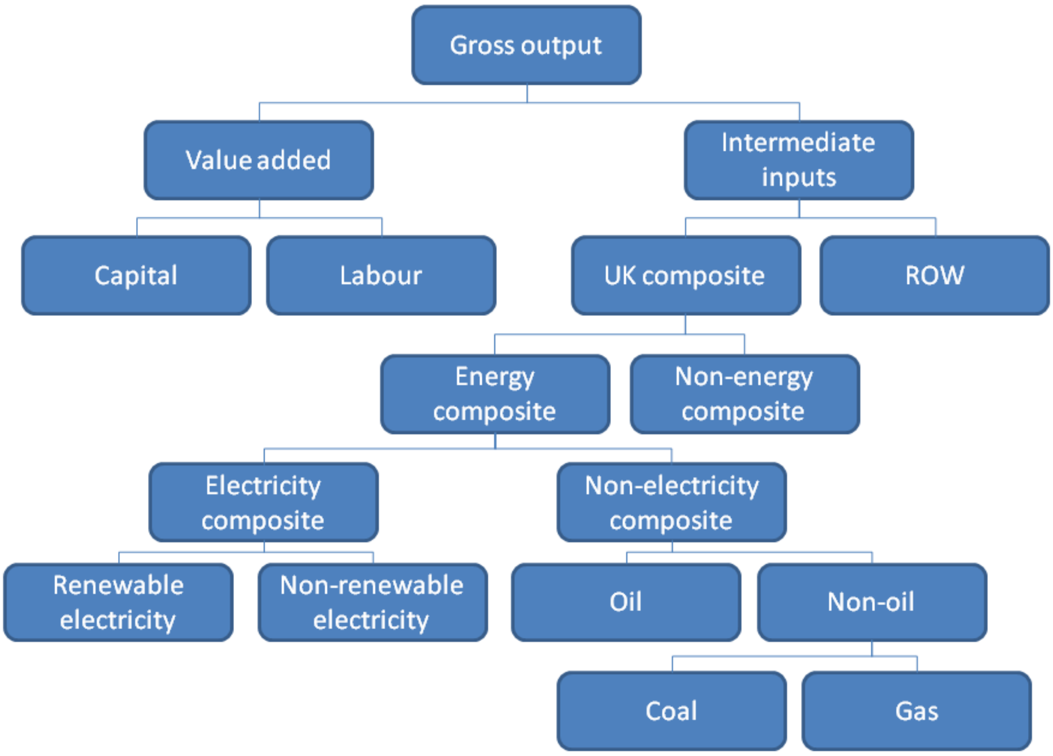
[41] We will see that in Paper six, there are different specifications of the production structure for the Electricity supply sector and for other sectors.

Figure 3: The multi-level production structure of the UKENVI CGE model



using hierarchical production functions. They note that there is a gap in the literature, in that there is little research into the significance of the alternative possible treatments of energy in these models (i.e. in terms of the "sensitivity of results to different specifications of hierarchical production functions"(Lecca et al., 2011, p. 2834)). Lecca et al. (2011) introduce energy into (alternatively) the intermediate inputs and value added blocks and introduce a simple export demand shock to the Scottish energy sector. Their results show that short-run results are affected by both the positioning of energy in the production function, and the elasticities of substitution between energy and other inputs, but that the results in the long-run are unaffected: results are "independent of elasticity values or the nature of the production structure" (p. 2837).

7.4.2 Database and parameterisation

The main database for the UKENVI model is a SAM built around an IO table for the UK economy. The SAM required the creation of income-expenditure accounts for 2000. The IO table itself was constructed for this project (see footnote six) as there was no analytical IO table for the UK published since 1995, as were the entries required for the creation of the SAM for the UK in 2000, and is explained in full in Appendix 2 of Allan et al. (2006). Here we focus on the construction of the IO table, including the disaggregation of the electricity sector.

An analytical Industry by Industry (IxI) table was required, to be consistent with the modelling specification which was also used in Hanley et al. (2006). This was produced in two stages: firstly, "rolling forward" the 1995 Product by Industry (PxI) tables to 2000 – to get the control totals for industrial gross output, and to then use a mechanical balancing program to produce an IxI table for the UK in the year 2000. Product by Product (PxP) tables for the UK in 1995 are also provided but these cannot be rolled forward as the Product totals are in purchaser prices (i.e. including distribution and trade margins, and taxes) and show the total value of products, whether produced locally or imported.

Second, the electricity sector in the UK IO database was disaggregated. Hanley et al. (2006) had explored the consequence of improvements in energy efficiency for Scotland and was the first application of the AMOSENVI model, with the treatment of energy inputs as described above. The disaggregation in Hanley et al. (2006) used experimental statistics from the Scottish Government which decompose the electricity sector in the Scottish IO table into five generation technologies, specifically nuclear, coal, gas, hydro and wind. In that paper wind and hydro technologies were aggregated to comprise the "Electricity – renewable" sector, while the other entries comprised the "Electricity - non-renewable" sector (Table 8). These were based on the (output, MWh) share of each technology within the generation of electricity in the Scotland. Column entries – showing the purchases made by each generation technology in Scotland – were constructed from various experimental databases to which which the statisticians at the Scottish Government had access. Row entries assumed that each sector purchased electricity from each of the five electricity generation sectors in relation to that technologies share in electricity generation. For Paper Five's application for the UK, we disaggregated the electricity sector within the UK accounts.

To use the information from the Scottish disaggregation to help the disaggregation in the UK tables required two steps. First, to remove intra-UK purchases from the import category for these technologies in Scotland, and reassign to (UK) purchases from sectors. Second, to adjust the contribution to the generation mix for each technology in the UK as a whole, which differs quite significantly from that of Scotland. For instance, in 2000 renewable technologies in Scotland produced about 10% of all output in 2000, but only about 3.5% for the UK as a whole, while there was a larger share for gas generation in the UK as a whole. Again, wind and hydro generation (and nuclear, coal, gas) were aggregated to form the "Electricity - renewable" sector (and "Electricity - non-renewable" sector), respectively. We will see in Chapter 8 an alternative disaggregation of the electricity sector in a CGE system, applied to Scotland.

7.4.3 Simulation strategy and assumptions

We increase the productivity of the energy composite in the production structure of all sectors, i.e. it is "energy augmenting technical change" applied purely to the use of energy in production activities, including energy sectors. This is introduced in the "central case" scenario of the model. Four points should be noted about the specifics of this scenario. First, the efficiency of energy in other consumption, for example, in households use of energy remains unchanged. This has important consequences for the scope of the modelling, and – as we will discuss later – distinguishes the modelling in this paper from some more recent work which has examined improvements in energy efficiency within households consumption of energy. As was seen earlier, household energy efficiency is an important focus of policy in this area.

Second, as noted earlier, a *ceteris paribus* improvement in factor productivity should act as a stimulus to economic activity. This could have the knock-on effect of increasing revenues for government as, for instance, employment and receipts of income tax would be higher, while reducing payments for social security, such as unemployment benefits. In the central case scenario the government's budget constraint is not imposed, implying that any additional revenues are not recycled within the economy, which would be consistent with government absorbing all of the additional savings.

Third, it is assumed that the improvement in the efficiency of energy use can be made "costlessly". Thus, the efficiency of energy use experiences a jump in levels which are not due to any investment by firms, or at a cost to government. This is referred to in the paper as "manna from heaven" – i.e. a miraculous and costless benefit. There is evidence that many improvements to energy efficiency that firms could make are not undertaken due to the existence of "barriers" (Sorrell et al., 2004). This literature identifies a range of factors preventing firms from improving their energy efficiency, which would otherwise appear to be an optimal improvement for the firm to make.

The assumption of a costless improvement in energy efficiency could, for example, be motivated in terms of one of these barriers being removed without cost. If it is, however, costly for the firm to make such improvements, this would limit the appropriateness of our assumption of a costless improvement. In recent work, Gillingham et al. (2015) defines this as a "zero-cost breakthrough" in contrast to a "policy-induced improvement" from an energy efficiency policy which is costly. They argue that modelling the consequences of zero-cost breakthrough would be useful for the attribution of impacts of an energy efficiency improvement, and that this approach "provides clear guidance for policymakers on how changes in energy efficiency alone would change energy use"

(Gillingham et al., 2015, p.4). On the other hand, specific energy efficiency policies will also change costs and attributes, aside from the change in the energy service cost, making it useful to understand the specific costs to the energy efficiency improvement.

Fourth, there are a set of assumptions imposed in the central case, and which are likely to be important for the empirical results of the existence and scale of "rebound". One of the main contributions of the paper is to explore the importance of model assumptions for the results. The paper explores not only the influence of model parameter and elasticity values on results, but also the specification of the labour market. Additionally, we consider the implications of "closing" the government budget constraint – and the alternative ways in which the additional revenues could be recycled within to the economy. Linking to the previous point, the sensitivity analysis also considers an extreme alternative to the "costless" improvement in energy efficiency. In a modelled alternative scenario, any improvements in energy efficiency which reduce firms costs are assumed to add to the labour cost to the firm. Specifically, we reduce the labour efficiency of firms' by an equivalent value to the savings implied by the improvement in energy efficiency in an exactly offsetting manner. We will see how important the alternative specifications modelled in this paper are for the results, and for establishing the types of sensitivity analysis which the flexibility of CGE models enables them to accommodate.

7.5 Contribution of paper five to the academic and policy literature

7.5.1 One of the first CGE applications to energy efficiency, and first for the UK

Greening et al. (2000) noted that, despite their usefulness, system-wide models had not been widely applied to understanding the consequences of improvements in energy efficiency, but that there was rather more evidence on direct rebound effects. Given this gap in the literature, and the obvious usefulness of exploring the scale of any "rebound" effect using CGE models, this has been a major research area over the last decade. Paper five was one of the first CGE applications to the issue of rebound from energy efficiency, and certainly the first empirical application to the UK economy, and followed the earlier application to the economy of Scotland (Hanley et al. (2006)). At the point of writing paper five, there were eight applications of CGE analysis to energy efficiency (including Semboja (1994); Dufournaud et al. (1994); Washida (2004); Grepperud and Rasmussen (2004); Glomsrød and Taoyuan (2005); Hanley et al. (2006)). A full review of CGE applications to energy efficiency research, as of 2007, is given in Allan et al. (2007b).

The types of economies studied in these papers range significantly across many domains, including the state of their economic development and scale (for instance, from the Sudan (Dufournaud et al., 1994) to Norway (Grepperud and Rasmussen, 2004)[42] and from Scotland with a population of just over 5 million (Hanley et al., 2006) to China (Glomsrød and Taoyuan, 2005) with a 2013 population of almost 1.4 billion (The World Bank, 2015). Additionally, and key to the appropriate modelling energy efficiency changes, these economies also differ in terms of the way in which energy is produced, consumed and used within the economy, and in the extent of trade. For example, Semboja (1994) examines the oil-importing economy of Kenya, while Hanley et al. (2006) model a Scotland which has significant electricity exports (which are themselves particularly energy intensive).

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[42] With a GDP per capita of $771 and $65,240 in 2013 (2005 dollars) respectively (The World Bank, 2015).

7.5.2 Rebound exists for the UK, and is lower in the long-run, than in the short-run

Paper Five reports that an across-the-board improvement in energy efficiency in industrial sectors has a short-run rebound of 62% and 55% for electricity and non-electricity domestic energy demands: the 5% improvement in energy efficiency leads to a short-run reduction in total domestic electricity demand of 1.92%. Rebound in electrical demand is calculated then as ((5-1.92)/5)*100, which equals 61.6%. Non-electricity energy demand therefore falls by more than electricity demand, meaning that rebound is lower in this energy type (recall that improving energy efficiency applies at the top level of energy goods in the production structure (Figure 3)). Rebound is present in the long-run, but the extent of rebound is lower – i.e. electrical and non-electrical energy demands fall by a greater amount, but not by as much as the improvement in energy efficiency. We find rebound of 27% and 31% for electricity and non-electricity domestic energy demands respectively in the long run.

The core results in this central case – finding rebound for the UK economy in response to an improvement in energy efficiency, and this being lower in the long-run than in the short-run – are therefore identical to the more recent "base case" findings of Turner (2009), which also used the UKENVI model, and an identical efficiency improvement. As well as being a useful robustness test of the reproducibility of the paper five's core results, Turner (2009) undertakes further sensitivity analysis of this finding. We explore the nature of the sensitivity analysis in paper five, and further developments in CGE analyses of modelling energy efficiency improvements in Section 7.5.3.

We look first at the short-run, which, recall, we define as a conceptual period in which capital stocks are fixed and immobile across all sectors, as is population (see Section 7.4). There is an increase in the demand for labour, which lowers the unemployment rate, and increases real wages (in the default, wage bargaining case). We would expect that sectors which are relatively energy intensive would see a fall in their relative price, which would improve their competitiveness in the long run. However, fixed capital stocks in the short run mean that capacity restrictions affect short-run prices in these sectors. Further, as capital stocks are fixed in the short run, the marginal cost of value added increases in line with output in the short run, increasing the price of value added and increasing the capital rental rate. Prices in the energy sectors fall sharply in the short-run, while output prices increase in the non-energy sectors as nominal wages are also higher. Turner (2009) explains that the "system-wide response to the drop in both effective and actual energy prices acts to offset the engineering or pure efficiency effect of the initial disturbance".

The short-run falls in the price of energy are significant. For instance, there are falls of more than 20% in the price of renewable and non-renewable electricity, while the price of gas falls by almost five per cent in this time period. Following the fall in demand and price in the short-run, there will be a (dis)investment response in these sectors which will mean that the long-run change in prices will be less than in the short run. In the long-run – in which sectors re-equate actual to desired capital stocks – these energy sectors therefore have a lower capital stock than in the initial equilibrium.

Writing in more detail on the adjustment within the energy sectors, Turner (2009) notes that this "disinvestment" effect in energy sectors "constrains the long-run rebound effect" (Turner, 2009, p.656). This result contrasts with the notion that rebound will always be larger in the long-run than the short-run, and reinforces the value of a CGE analysis of these changes. For instance, Turner (2009) contends that theoretical arguments, such as Wei (2007), that rebound is larger in the long-run than the short run may rely on unrealistic assumptions, and not take account of feedback effects, such as the consequences of the fall in the price of energy on sectoral profitability (and so investment).

In the long-run, the prices of output in all sectors are lower (despite increases in real and nominal wages) while price reductions are lower in energy sectors due to the changes to capital stock. The fall in sectoral prices for non-energy sectors typically reflects the scale of energy use in those sectors – with largest falls seen in Manufacturing sectors – while the largest reductions in prices are seen in energy sectors. A consequence of falling output prices is that the output of all non-energy sectors increases in both the short and long-run, most notably those which have higher energy usage, and especially those which are traded internationally. Overall, in the long-run there is an 0.21% increase in exports, with a similar change in total employment, and GDP increases by 0.17% compared to the initial value. Our empirical findings therefore suggest that there is an unambiguous economic dividend from improving energy efficiency. It is however to be expected that these results arise due to the nature of assumed interactions and behaviours within the economic system, and therefore may not be a general result.

7.5.3 A first focus on the sensitivity of rebound results

A further contribution of the paper was to provide sensitivity analysis on the specific nature of assumptions and structural data, for instance in the base year values of the SAM for the UK, as well as the key parameter values. As noted above, there were at time of writing various applications of CGE models to energy efficiency, with each model being different in a number of dimensions. This made comparisons across model results difficult, as it was impossible to say how important the details of model structure or specification were for the observed results. Paper Five identified three key parameters which are likely to be critical for the modelled results:

- the elasticity of substitution between energy and non-energy intermediate composites
- the elasticity of substitution between value added and intermediates

- the elasticity of export demand

Before proceeding, we should be clear about the rationale for and the nature of the sensitivity analysis being undertaken here. Specifically, we are concerned that the economic relationships specified in the CGE model, particularly the parameters used, will have an impact upon the results of the analysis. As described earlier, some parameters may come from econometric estimation, while others will be "best-guesses". Those data that come from econometric work may not additionally be directly estimated for the economy of interest (but might, e.g. come from other regions or other nations, perhaps of a similar scale or economic structure) or could be from the appropriate economy but not from the most recent data.

Sensitivity analysis therefore requires that the specific parameters used in the simulations are varied and the models re-run, revealing the importance of specific assumptions (or at a minimum, the scope for results to be significantly affected by particular parameters). This could be termed as "limited sensitivity analysis", which is "any ad hoc procedure used to evaluate the sensitivity of model results to the elasticities used" (Wigle, 1991, p.36). Despite being more limited that other forms of sensitivity analysis (such as more Systematic Sensitivity Analysis[43]) a useful outcome of limited sensitivity analysis is clearly to identify the parameters which are most important for model results and so identify research priorities for further econometric research.

The first area of sensitivity is substitution between energy and non-energy goods. Saunders (2008) argues that rebound is more likely the larger is this elasticity, implying a greater degree of substitution between energy and non-energy inputs. The results of the sensitivity analysis support this, and show that the long-run results for rebound are

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[43] This would include "Conditional" or "Unconditional" SSA where Conditional SSA means repeating simulations "moving each and every elasticity away from its point estimate while holding all others at their point estimate" (Wigle, 1991, p.37) while Unconditional SSA involves many more simulations, varying each elasticity over a given range (informed by the standard error for that estimate). In practical CGE applications, Haddad and Hewings (2005) undertakes such robustness checks to parameter values and exogenous shocks, while Phimister and Roberts (2012) examine the results sensitivity to trade and production elasticities.

significantly affected (while the economic impact on GDP and employment is less sensitive). Additionally, with more elastic substitution parameters in all sectors between value added and intermediates, firms are able to shift production towards the cheaper intermediates (including energy) and we find greater rebound in (both forms of) energy demand, and a slightly lower GDP impact. Increasing the elasticity of export demand however – which makes exports more responsive to price changes – has no significant impact on the degree of rebound. This is explainable by the small changes in prices across all non-energy sectors, and the low levels of exports of energy products from the UK. Similar analysis for Scotland, which is a significant electricity exporter to the rest of the UK, shows that increasing the responsiveness of export demand to change in prices is sufficient to generate backfire (Hanley et al., 2006).

Turner (2009)'s greater sensitivity analysis varied (jointly) elasticities of substitution and trade (i.e. the Armington elasticities). That paper reveals the extent to which the results noted earlier, i.e. that rebound was greater in the short- than the long-run, is a general finding. Specifically, that paper finds this result holds generally when substiution parameters are more elastic and for lower values of trade elasticities. Further, this sensitivity analysis also shows that backfire can arise in the short- and long-run, and particularly when elasticities of substitution in production are greater than 1 (the sensitivity in Paper Five only examined values of 0.1 and 0.7 around central case values for elasticity parameters). Thus, we can say that this paper identifies areas where further analysis was important, while other authors have begun to explore the extent to which the findings can be generalised.

There continues to be a rapidly growing literature on the application of CGE approaches to answering the empirical scale of rebound and backfire effects following improvements in energy efficiency in production[44]. Some of these use the same framework as paper

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[44] There are also applications of CGE analysis to changes in the efficiency of energy use in domestic, rather than industrial, uses, such as Lecca et al. (2014). However, we abstract from these papers as the focus of paper five is on improvements in efficiency in the industrial use of energy.

five (AMOS), albeit for Scotland rather than the UK, e.g. Hanley et al. (2006, 2009); Turner and Hanley (2011).

8 CGE modelling of Environmental Tax Reform and the "double-dividend"

Earlier, we saw how CGE models can be usefully employed in the analysis of demand-side disturbances (Chapter 6) and modelling the consequences of energy efficiency improvements (Chapter 7). In this Chapter we explore the application of CGE models to the area of Environmental Tax Reform (ETR), and the contribution of Paper Six: this was published as Allan et al. (2014b). As described briefly in Section 3.2.5, Paper Six examines how the global externality of atmospheric emissions can be approached by national governments through the introduction of a carbon tax so that firms internalise the social costs of their pollution activity.

This Chapter proceeds as follows. First, Section 8.1 describes the economic rationale for ETR and defines the "double-dividend". Section 8.2 then explores which particular features of CGE models make them useful for understanding the consequences of changes in carbon taxes. Section 8.3 describes the particular features and results from the AMOS model of Scotland employed in Paper Six.

This model has significant extentions to the sectoral disaggregation of the SAM upon which it is based – specifically to the electricity sector, including generation disaggregated by generation technology – and a unique characterisation of separate production functions for the electricity supply sector and the other sectors in the economy. Section 8.4 evaluates the contribution of Paper Six to the academic literature on the CGE modelling of ETR, including the existence of a double-dividend under certain conditions – including the form in which revenues from a carbon tax are returned to the economy – and to a key policy question, specifically, how the credibility of energy policy helps achieve emissions reduction goals in a more timely manner.

8.1 The case for environmental tax reform, including a carbon tax

Since Arthur Pigou's groundbreaking work (Pigou, 1920) economists have analysed the issue of "externalities". These arise when the activities of (utility-maximising) private agents (i.e. firms or households) produce outcomes which are different from those which would be welfare enhancing for the population as a whole.

We are particularly interested here in the specific example of the (negative) externality of atmospheric emissions. In the presence of emissions from production, the unrestricted market outcome would produce a level of emissions which was greater than that which would be socially optimal (i.e. the marginal social cost curve is to the left of the marginal private cost curve). This is therefore a negative externality, in that emissions place a cost on current and future generations through contributing to atmospheric emissions and global climate change.

Pigou's insight was that, through introducing an appropriate cost to the externality, the private agent would internalise the external cost of their decision and the private market outcome would equate to the social outcome. With an appropriate price (e.g. a tax on the carbon content of fuels) private and social optimal outcomes would converge[45].

Pearce (1991) notes specific advantages for a carbon tax[46]. First, such a measure would minimise the cost of reducing emissions, by reducing emissions where the cost of doing so would be cheapest. Emissions would be reduced where the cost of carbon abatement was less than the tax, while producers for whom reducing emissions was more expensive

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[45] A conceptually alternative approach would be to introduce property rights into the market so that, for this example, the "ownership" of the global atmosphere would rest with an entity which would hold the right to pollute and could sell these – at a cost – to those wishing to pollute. Schemes such as pollution permits are examples of this alternative approach to removing the consequences of an externality. (Pearce, 1991, p.940) does not discuss tradeable permits, aside from noting that "taxes have some practical advantages over permits".

[46] Pearce (1991) also discusses: the role of taxes in providing an incentive to firms to continuously innovate with regards to their energy consumption – which has efficiency benefits over introducing "standards" on products –; the ease of modifying taxes to ensure they are set correctly, and; the possibility of applying a global tax and revenue-sharing across international boundaries. As these are not the focus of the modelling literature on carbon taxes, we do not develop them further here.

would pay the tax rather than abate.

Second, he notes that an appropriately set tax would be revenue-raising and might be used to reduce taxes in other markets. An effective carbon tax could raise “significant” revenue, which would need to be returned to the economy so as to not “alter completely fiscal stances by governments”. He writes that a specifically designed revenue-neutral tax on carbon could also be more likely to be politically acceptable (Pearce, 1991, p.940):

> “Governments may then adopt a fiscally neutral stance on the carbon tax, using revenues to finance reductions in incentive-distorting taxes such as income tax, or corporation tax. This ’double-dividend’ feature of a pollution tax is of critical important in the political debate about the means of securing a ’carbon convention’. Industry will resist any new tax. Politicians are understandably nervous about introducing such taxes. But the corporate and public acceptability of such a tax is greatly enhanced if the tax is introduced as part of a ’package’ of fiscally neutral measures.”

We will see later (Section 8.4) that the academic literature on the *ex ante* modelling of carbon taxes has shown that the way in which the revenue is returned to the economy to ensure revenue-neutrality is of fundamental importance for the existence and scale of the second (economic) “dividend”. Before examining the usefulness of CGE models in exploring the environmental and economic impacts of carbon tax, we briefly define what is meant by a “double-dividend”.

8.1.1 Defining the double-dividend

Bovenberg and van der Ploeg (1993), cited in Patuelli et al. (2005), define a double-dividend thus:

> “The hypothesis that higher pollution taxes associated with more environ-

> mental concern would not only improve the environment but also boost employment (and hence the tax base)"

Bovenberg and Van Der Ploeg (1998, p.293) similarly define a double dividend as: "not only an improvement in environmental quality but also a boost to employment".

Further, in an early and influential survey of ETR from a public finance perspective, Goulder (1995) distinguishes between three claims of the double dividend hypothesis, which he refers to as the "weak", "intermediate" and "strong" form. The "weak" form refers to where introducing environmental taxes and using revenues to "finance reductions in marginal rates of an existing distortionary tax, one achieves cost savings relative to the case where the tax revenues are returned to taxpayers in a lump-sum fashion" (Goulder, 1995, p.159). He argues that this form of the hypothesis is uncontroversial – if an existing tax is distortionary then almost by definition reducing this tax would be more beneficial than a lump-sum transfer. The "intermediate" and "strong" form concepts of the double dividend refer to the notion that "swapping an environmental tax for a distortionary tax involves a negative overall gross cost" (Goulder, 1995), where gross cost refers to the "welfare sacrifices associated with environmental tax policies", i.e. the economic, and individual, welfare (abstracting from any welfare derived from the improvement in the environment) of making an environmental tax reform package increases (or at least does not decrease) welfare.

It is clearly anticipated that a tax on carbon use would reduce the use of fuels, and so reduce emissions across an economy. The incidence of the tax would vary across industries and households in relation to their initial carbon-intensity of production. Raising the price of goods (fuels) in the consumption of which carbon was emitted would reduce the use of these inputs and so reduce emissions. This is the "first" (environmental) dividend from the carbon tax. It is perhaps useful to note that the definition of Bovenberg and van der Ploeg (1993) does not however note that emissions are reduced, rather that there is an improvement in the (somewhat) broader "environment". This first dividend is, however, typically inferred from a change in CO2 emissions.

With regard to the second (economic) dividend, the two definitions above unambiguously highlight the impact on employment rather than other economic variables, while Goulder (1995) stresses the welfare impacts. As we saw in Chapter 1, employment is likely to be of broad interest to the policymaker, but other economic variables are likely to be of equivalent priority, such as GDP. As Patuelli et al. (2005, p.556) notes, most studies declare the existence of an economic dividend with "a gain in employment, although some of them prefer to search for welfare and economic benefits". Similarly, Bosquet (2000, p.24) writes that which ever measure is used, "the distinction matters as changes in welfare and employment do not necessarily coincide". To simplify this point, however, we note that in his survey of the modelling literature on the double dividend, Bosquet (2000) observes that employment and GDP impacts are more frequently reported in such studies.

8.2 The value of CGE analysis of a carbon tax

There have been a number of reviews of modelling approaches used to analyse the environmental and economic consequences of a carbon tax (e.g. Patuelli et al. (2005) and Bosquet (2000)). A number of different model types have been applied to the issue of environmental tax reform; for instance, Bosquet (2000) identifies applications using "partial equilibrium, computable general equilibrium, macroeconomic, input-output, etc." techniques. Indeed, in that review of the literature, he find that while most studies find an environmental improvement (i.e. a fall in CO2 emissions) there is no evidence that the model type affects the sign of the second (economic) dividend. Three-quarters of the macroeconomic modelling applications find a positive economic impact, while this is also true for 88% of the (smaller sample of) CGE applications in his analysis. A second "meta-analysis" of ETR (Patuelli et al., 2005, p.576) however did find that CGE models "show more system-wide positive effects on the economy". This latter paper reviewed twenty-five CGE applications of environmental tax reform.

Computable general equilibrium (CGE) and macroeconomic models are the two model forms most commonly applied to understanding the impacts of ETR (Patuelli et al. (2005)). We have already argued for the benefits of flex-price techniques, such as CGE, in examining energy and economic impacts of environmental technologies and policies (Section 2.3). As Patuelli et al. (2005) notes, the difference between CGE and macroeconomic models is most obvious in the approach to simulating the economy. Macroeconomic models primarily focus on the level of activity across the economy as a whole, and not individual, interdependent, sectors (Patuelli et al., 2005). Macroeconomic models are also typically generated from time-series cross-sectional econometric models, requiring significant amounts of data. The availability of data therefore can be an important impediment to the creation of macroeconometric models.

8.3 Modelling the introduction of a carbon tax in a CGE model of Scotland

Having discussed the economic case for a carbon tax (Section 8.1) and the definition of the double (i.e. environmental and economic) dividend that could result (Section 8.1.1), we now turn to describe the application of Paper Six (Allan et al. (2014b)). The following section (Section 8.4) will place the approach used, including the ways in which the revenues are recycled, and the models findings, in context, alongside other CGE applications to carbon taxes, and assess the contribution of Paper Six to the academic literature.

8.3.1 The AMOSENVI model

Section 6.3 described the AMOS model which was in both Papers Three and Four (Gilmartin and Allan (2015) and Allan et al. (2014a)), while Section 7.4.1 presented the details of the model from Paper Five (Allan et al. (2007c)). Paper Six, on the other hand, uses the AMOSENVI model, which is a large-scale, multi-sectoral energy-economy-environment computable general equilibrium model, which is an appropriately extended version of the AMOS model. As this section will describe, AMOSENVI is specifically designed to permit the analysis of energy and environmental consequences alongside economic changes. As the AMOS model was described earlier, this section will provide additional details of the model which was used in Allan et al. (2014b), and will detail specifically those areas where the AMOSENVI model differs from the model used in papers three and four.

8.3.2 Production structure

We saw earlier that in the AMOS model, producers were assumed to minimise costs subject to "nested" production functions, while permitted substitution (typically using a CES specification at each level ofthe production hierarchy) between inputs in response to changes in the relative price of inputs. The same principle is applied in AMOSENVI, and UKENVI, however in the specification of the model in Paper Six, there are two alternative production functions. The production structure for the electricity sector is shown in Figure 4, while that for all other sectors is shown in Figure 5. Like Paper Five therefore, in this model there is disaggregation of the electricity sector, however, as we shall see the disaggregation itself differs in that this model separately identifies generation and non-generation activities.

In the production structures in this model for the electricity and non-electricity sector, value added and intermediate inputs combine to produce sectoral total gross output, with value added a CES function of capital and labour. At the intermediate inputs level, sectors combine energy and non-energy inputs, with energy split into electricity (referred to as "transmission" although this also includes distribution and supply) and non-electricity energy. Non-electricity energy is combined in both production structures between oil and non-oil, with non-oil further combined from gas and coal inputs.

Where the production structures differ is in the consumption of electricity. For the electricity supply sector (Figure 4) the model distinguishes between transmission and generation, before generation is further disaggregated to intermittent and non-intermittent generation technologies. We describe the unique database on which this disaggregation is based in Section 8.3.3. Here we note that this disaggregation of the electricity sector, including specific generation technologies within the nesting of the electricity supply sector has useful features.

First, it reflects in greater detail the range of generation options facing the electricity supply sector. Second, it more closely aligns with the market arrangements for electricity generation and supply. The configuration of earlier versions of AMOS, for instance, assume that each technology generating electricity is producing a "technology-specific" output, e.g. nuclear electricity, or coal electricity, each which has its own price. Other sectors directly purchase this technology-specific good for their own activities.

Third, there is an explicit acknowledgement of the importance of accounting for non-generation activities within the electricity sector, which are captured within electricity "transmission" (which also includes distribution and supply activities[47]). Disaggregations by technology in earlier work (e.g. Paper Five) implicitly assumes that each generation technology also has a unique transmission, distribution and supply arrangement.

8.3.3 Database and parameterisation

We described earlier (Section 6.3.7) how consumption and investment is characterised in both the myopic and forward-looking specifications in the AMOSENVI model. In Paper Six, the model employed is that with forward-looking behaviours. In sensitivity analysis

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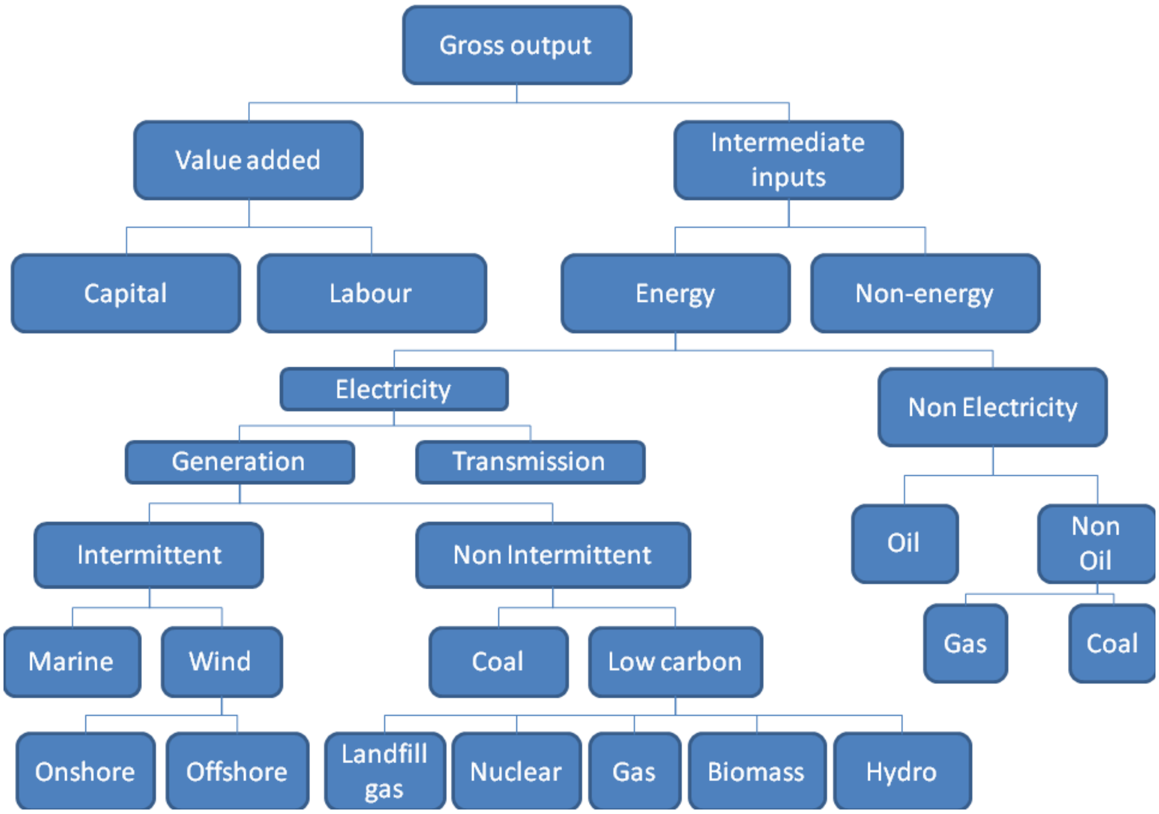
[47] These include, for example, a range of activities from grid-related areas such as management, extension and maintenance, through to domestic supply contracting and sales.

Figure 4: The multi-level production structure for the electricity supply sector in the AMOSENVI model

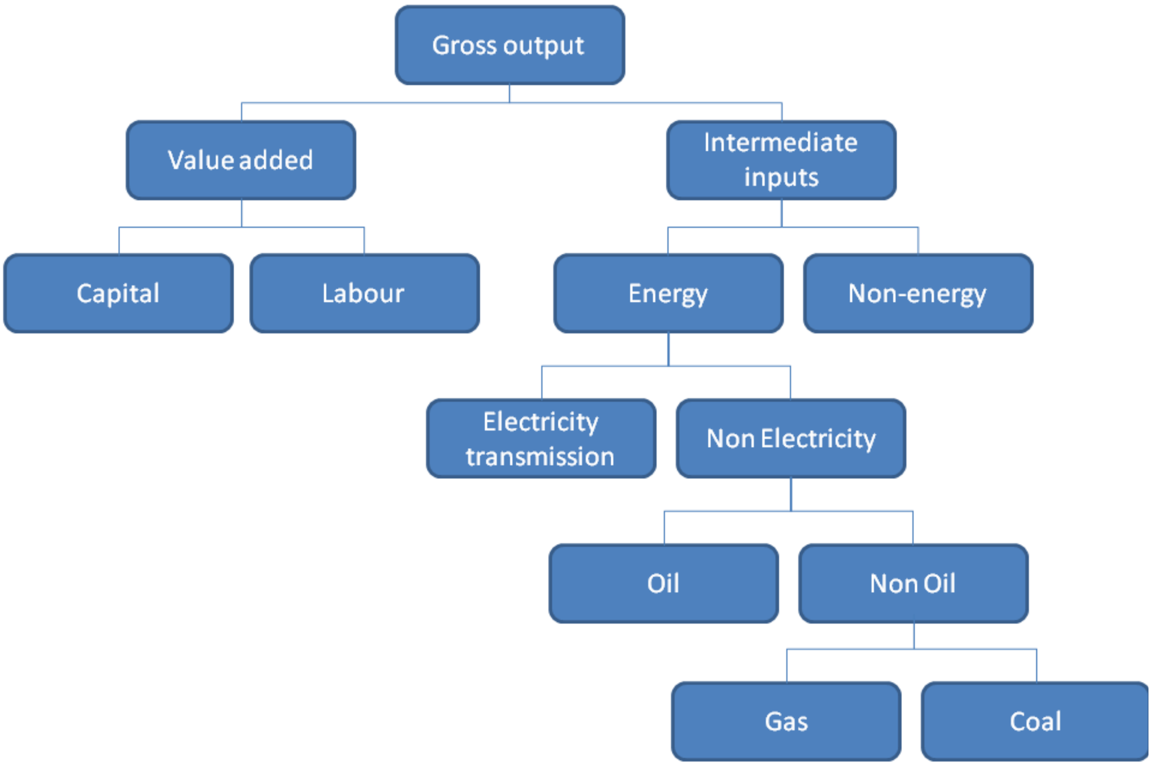


reported later (Section 8.4) we test the importance of this choice for the results.

Paper Six considers wages as determined through a bargained real wage function (Layard et al., 1991) – as in Papers Three and Four – and as described in Section 6.3.5. Real wages and unemployment are inversely related - with increases in labour demand raising real wages and reducing the unemployment rate. Migration between Scotland and the rest of the UK is permitted and assumed to, again, respond to differences in real wages and unemployment rates.

The model is calibrated on a Scottish SAM for 2000, which has a detailed representation of the Scottish electricity sector, including disaggregation of the electricity generation sector (Allan et al., 2007d). There are seventeen sectors in AMOSENVI, of which nine are electricity generation technologies, one is the electricity supply sector (specified

Figure 5: The multi-level production structure for all other sectors in the AMOSENVI model



with the alternative production structure described above) and there are three (non-electricity) energy sectors (coal, oil and gas). The remaining four sectors comprise aggregations of the rest of the Scottish economy. The sectors identified in the model, with the original sectors from the Scottish IO table, are given in Table 9.

This disaggregation of the electricity sector in the Scottish IO table is novel, and is fully described in Allan et al. (2007d). This paper notes that the Scottish Government have a history of developing IO tables for Scotland and that these can be used to understand the economic consequences of policy and non-policy disturbances. Additionally, it identifies that the Scottish Government has ambitious renewable electricity targets, that these will produce significant changes in the composition of electricity generated in Scotland and that an IO table provides a useful way to consider the economic impacts

Table 9: Sectoral aggregation for Paper Six

Sector	Sector name	Sector in Scottish IO tables
1	Primary	1 to 3, 5 to 7
2	Manufacturing	8 to 34, 36 to 84
3	Utilities and transport	87 to 88, 93 to 97
4	Services	89 to 92, 98 to 123
5	Coal extraction	4
6	Oil refining and treatment of oil and petroleum products	35
7	Gas	86
8	Electricity transmission, distribution and supply	85
9	Generation - nuclear	85
9	Generation - coal	85
9	Generation - hydro	85
9	Generation - gas	85
9	Generation - biomass	85
9	Generation - onshore wind	85
9	Generation - offshore wind	85
9	Generation - landfill gas	85
9	Generation - marine	85

that could follow these changes.

The major issue with the use of the Scottish IO table to analyse changes in the electricity sector however is that the identified “Electricity” sector in the economic accounts, aggregates together all activities within the electricity production chain, including generation, transmission, distribution and supply, and so does not identify individual generation technologies. This aggregation is clearly inappropriate given that part of the purpose of a carbon tax is to lead to a shift in the composition of generation towards low carbon technologies. The disaggregation of the sector creates a row and column for each generation technology from survey and non-survey data for electricity generation technologies in the year 2000 in Scotland, and separately identifies these in the Scottish IO tables for that same year. By identifying the linkages of the generation components, this approach also separately identifies the non-generation elements (i.e. transmission, distribution and supply) of the sector (Gay and Proops, 1993; Cruz, 2002, 2009; Vendries Algarin et al., 2014).

Recent work has argued that, for environmental analysis, disaggregation of the IO accounts to areas of environmental interest is superior to working at a higher level of aggregation. Lenzen (2011, p.73) for example, suggests this is particularly true when the more disaggregated activities are "heterogeneous with respect to their economic and environmental characteristics", as is clearly the case with electricity generation technologies. Allan et al. (2007d) show that - as well as quite different direct emissions intensities - generation technologies have quite different linkages to the regional economy.

The disaggregation of the electricity sector into generation and non-generation activities is different to that used in, for example, Limmeechokchai and Suksuntornsiri (2007) and Shrestha and Marpaung (2006). In these papers, the electricity sector in Thailand and Indonesia respectively, is disaggregated into technology-specific activities and do not separately identify non-generation activity. The resulting disaggregated IO tables are then used to illustrate the economic and environmental consequences of changes in the electricity generation mix.

Some recent empirical work on the disaggregation of the electricity sector within an IO system has however continued to use this assumption, despite its clear limitations in understanding the economic and environmental contribution of electricity generation activities. For example, Lindner et al. (2012) demonstrates a technique to disaggregate the electricity sector using limited information and applies this to separate the electricity sector in an IO table for China into three components: hydroelectricity; sub-critical coal and other fossil fuels. The limitations of this assumption, is however well understood by these authors. For instance, (Lindner et al., 2012, p.339) explicitly acknowledges that their disaggregation:

> "assume[s] that the transmission and distribution sector is merged with the energy generation sector, and thus the potential effects of this intermediate sector are disregarded. In reality, this would only hold true if each generation unit had its own unique network, which is not the case."

8.3.4 Simulation strategy, including recycling options

The tax on carbon emissions is introduced as a constant and *ad valorem* tax on the use in intermediate production of coal, oil and gas. These inputs can either be imported or domestically produced, however the tax is imposed on the use of these goods in production sectors in Scotland. As the carbon content of each fuel differs, the specific tax rate which applies to each sector will vary. The taxes are introduced in the first period and maintained at the same level over the simulation.

Critically, as well as addressing the externality of climate change, the tax raises revenue for the government. In Paper Six we introduce a tax of £50 per tonne of CO2 which generates a total tax take of £1,662 million in 2000 prices. This is equivalent to 6.7% of total tax revenue and 2.5% of GDP in the base year of the model, and which is, as Pearce (1991) indicates carbon taxes could be, a significant source of revenue[48]. Given the scale of these revenues, it is therefore natural to consider scenarios in which these revenues are recycled back into the economy, so as to leave the overall fiscal stance of the government unchanged (Pearce, 1991).

The level of the carbon tax introduced is selected by iteration. As was discussed in Section 3.2.5, the Scottish Government have a target of reducing CO2 emissions in Scotland by 42% by 2020, relative to 1990 levels. This corresponds to a reduction of 37% on the level of CO2 emissions in the base year (2000) of this version of the AMOSENVI model.

The paper considers three alternative scenarios for the use of the carbon tax receipts. The first of these sees the additional revenue not recycled back into the Scottish economy (i.e. the tax is "revenue positive" for the government (Pearce, 1991)). This would be consistent with the revenue from the tax being put towards government savings, or

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[48] At this scale, the hypothetical ETR package in Scotland is similar to that introduced in Denmark in 1994 (as shown in Table 1 in Bosquet (2000)), which raised taxes on gasoline, electricity, water, waste and car – revenues that were recycled through personal income tax – and on CO2 and SO2, where these revenues were returned through reductions in social security contributions.

the revenues from a Scottish-specific carbon tax being transferred to the UK government with no compensating adjustment to Scottish government revenues[49]. Although an unlikely scenario for a carbon tax – not least for the political consequences of such a change to the tax system - this serves as a useful benchmark scenario in which the pure effect of the carbon tax (without any recycling of the carbon tax revenue) can be considered.

This has an unambigiously negative impact on the Scottish economy. By increasing the price of fuels used in production, the demand for fuels decreases, contracting production across the economy. The demand for labour falls, lowering employment (increasing unemployment) and lowering the real wage, which encourages out-migration from Scotland. In the long-run, i.e. once labour and capital stocks have fully adjusted, the labour force will be lower than its initial level, and the real wage will return to its initial level, but at a higher nominal wage with a persisting negative effect on the competitiveness of economic output from Scotland. Clearly, the primary policy motivation behind a carbon tax is to bring about a fall in emissions related to the use of carbon, and we will see later whether the these anticipated negative economic consequences coincide with falls in the level of emissions.

In the second and third scenarios, the carbon tax is revenue-neutral for the government accounts in Scotland, with all proceeds from the carbon tax recycled back to the Scottish economy. The way in which the revenues are returned to the Scottish economy is different in both these scenarios however. In the second scenario, the revenue is returned through a step increase in the level of (current) government spending in Scotland. The amount of taxation revenue received is distributed across Scottish sectors in the same proportions as initial Government spending. This spending has purely demand-side consequences, in that it increases government demand for the output of sectors in the

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[49] Goulder (1995, p.272) suggests that for a national CGE model, this use of the revenues would be "equivalent to reducing future taxes, assuming that the government's debt cannot indefinitely grow faster than the interest rate". This is however of limited applicability in the case of a small open regional economy that does not issue debt.

Scottish economy, stimulating changes in prices, output and adjustments in sectoral levels of capital and labour factors of production.

In the third scenario, government budget revenue-neutrality is imposed through lowering the (average) rate of personal income tax (i.e. the tax on labour). Given the scale of the revenues of the carbon tax, the rate of income tax is reduced by 6.16% in the short-run and 5.37% in the long-run compared to its base year values. With a regional labour market characterised by wage bargaining, this lowers the cost of labour to industries with, *ceteris paribus*, the demand for labour increasing for each level of output, encouraging employment, increasing the real wage rate and lowering the unemployment rate. This stimulates migration to Scotland, expanding labour supply which lowers the real wage and restores equilibrium in the labour market at a higher level of population and economic activity. The empirical question remains whether either method of revenue recycling gives rise to a double dividend, in terms of positive economic impacts at the same time as reductions in the level of CO2 emission produced in Scotland. We discuss how the results of Paper Six contribute to the academic literature and questions of policy in Section 8.4.

8.4 Contribution of the paper to academic literature and policy questions

8.4.1 There is an environmental improvement from a carbon tax - the "first" dividend

The first contribution of Paper Six is to demonstrate that, as expected, the modelled carbon tax produces the first (environmental) dividend a reduction in CO2 emissions. In all three scenarios the level of emissions are reduced by (at least as much as) the targeted 37% reduction in CO2 emissions between 2000 and 2020.

The results are firstly shown for the short- and the long-run. These are defined as (static) conceptual time periods, rather than a defined number of years, for instance. The short-run corresponds to the first period following the introduction of the carbon tax, in which capital stocks and population are fixed at their base year values. We will discuss the simulation results from the dynamic specification of the same model in Section 8.4.3. Across each simulation, the long-run change in CO2 emissions is greater than 37%.

The short-run change in CO2 emissions is less than the long-run fall in each case. This occurs as in the short-run the capital stocks for each sector are fixed. Over subsequent adjustments between the short and long run, sectors change their capital stocks, with sectors for whom the return on capital is now lower – typically the carbon-intensive fuel, including fossil electricity generation sectors – decreasing their capital stocks.

Such findings are in line with Bosquet (2000, p.23)'s survey of the modelling of ETR, which finds that "ETR appears to influence the environment positively". In his review, the majority of *ex ante* simulations found an emissions reduction, with the mode of CO2 reductions observed in these papers as between zero and 5%. This concurs with Patuelli et al. (2005, p.577)'s finding that "the environmental effect of ETR is consistently evident in terms of CO2 reduction". This is also in agreement with studies published later than these reviews including Wissema and Dellink (2007) who find that a carbon tax in Ireland of €40 per tonne of CO2 could reduce emissions by up to 50%, while a uniform tax on energy at the same rate could reduce emissions by more than 25%[50].

An additional contribution is that the fall in CO2 emissions is invariant to the existence or form of recycling, which is in line with the findings from other models. Patuelli et al. (2005) find that whatever form the tax takes – an energy tax or a CO2 tax – recycling does not have an impact on the existence or size of the environmental dividend. We shall see in the next section that the form of recycling matters for the second (economic)

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[50] Interestingly, this paper did not consider the additional consequences of revenue recycling.

dividend.

8.4.2 The way in which revenues are "recycled" matters for the second (economic) dividend

As discussed above, as well as addressing the externality of carbon emissions, it has been noted that the revenues from a tax can be returned to the economy, and that this this could have beneficial impacts (e.g. Pearce (1991)). This "double dividend" literature notes that the way in which such revenues are returned to the economy can be critical in producing such an effect. Goulder (1995) noted that the way in which revenues are returned to the economy could be important, and that earlier studies had assumed a lump-sum transfer of taxes.

If these revenues were to be used to reduce other taxes, this could produce improvements in distortionary taxes, or taxes limiting an economic "good", such as employment. Goulder (1995) finds returning the revenue through reducing a number of (personal, corporate, and payroll) taxes has a significant impact on the economic impact of the carbon tax introduced. In no case however, does the ETR package of the carbon tax and the alternative "revenue replacement" route produce an overall positive impact on welfare. The form of recycling which has the largest (i.e. most positive) impact on welfare is a reduction in payroll tax.

Patuelli et al. (2005, p.576) explain why lump-sum transfers fail to provide the same (as positive) impacts on economic variables as other interventions in existing taxes. They write:

> [lump-sum transfers] are one-off interventions that do not affect the economy as much as structural policies such as labour cost policy.

Our results confirm that recycling matters for the existence (and scale) of the second (economic) dividend from ETR. If we focus on the long-run results, we find that key economic variables show negative impacts under the scenario when taxes are not recycled within Scotland: GDP falls by 2.68% from its initial values, while employment falls by 2.60%.

When the revenues are recycled through increasing government expenditure, this introduces a positive demand shock which only partially offsets the fall in economic activity from the carbon tax. The resulting impacts on GDP and emploment in the long-run are lower than in the base year values. The interaction in the labour market between the negative impact on economic activity from the increase in the cost of production reducing demand for labour, and the demand shock, leads to an overall reduction in the demand for labour, a fall in real wages and an increase in unemployment. Migration re-establishes equilibrium in the labour market, but at a lower level of employment and economic activity.

When recycling the revenues from the carbon tax by lowering the average rate of personal income tax we find that there is a second dividend: an increase in employment (as well as an increase in GDP) relative to the base year. The level of GDP increases in the short- and long-run by 0.26% and 0.83% respectively. The reduction in the rate of income tax serves to increase the demand for labour (as labour is now relatively-cheaper) and reduce the unemployment rate. This increases real wages in the short-run, in which population is fixed in aggregate but labour is mobile across sectors. Some exports are crowded out by the increases in prices in the short run, falling by 0.29%.

However, the lower unemployment rate and higher real wages in Scotland induce net in-migration to Scotland, which eases the tightness in the labour market and puts downward pressure on real wages. The long-run equilibrium in the labour market is thus restored through in-migration and an expanded labour supply relative to base year values. There is a lower nominal wage in the long-run, as a result of workers bargaining on restoring their real take home wages which – with a lower income tax rate – are now consistent with a lower nominal wage. The combination of a lower nominal wage, and an increase in labour supply, produce a higher level of household consumption and a small positive increase in exports in the long-run.

Such a result is consistent with other papers. For example, Patuelli et al. (2005)'s review notes that the majority of papers considered find a small (positive or negative) economic impact, but that the the mode of recycling matters. They report that reductions in labour taxes and reductions in Social Security Contributions produce more positive impacts than reducing personal income taxes, as the former directly affect the profitability of firm's investments.

The reduction in the average rate of personal income tax is similar to the treatment of the revenues from the carbon tax employed in a number of papers (e.g. Holmlund and Kolm (2000); Bor and Huang (2010); Manresa and Sancho (2005)). Drawing examples from some of these, Bor and Huang (2010) return revenues through individual income tax, business income tax or through (equally) reducing both these taxes. Their most positive second (i.e. economic) dividend is found when individual income taxes are reduced. In all their simulations however the sign on the second dividend, when measured in terms of employment, is negative; however they do report positive changes in the long-run for GDP under reductions in personal income tax and when business and income taxes are both equally reduced.

Manresa and Sancho (2005) model the impact of reductions in payroll taxes, and find that imposing "ecotaxes" while reducing labour taxes produces a double dividend. In their simulations they have a similar specification of the labour market in that real wages are higher (lower) when the unemployment rate is lower (higher), with their "β" variable determining the responsiveness of real wage to the unemployment rate. They model both a "fixed" model, i.e. where β is zero, implying that the unemployment rate is fixed and the wage rate is "fully flexible", and a "flexible" model where β has a value of 1.25, where changes in the unemployment rate will lead to changes in the wage rate (and where a higher value suggests that the wage rate is more sensitive to changes in the unemployment rate). This “flexible” specification is thus similar to the regional bargaining specification adopted in Paper Six.

Under the flexible specification of the model, Manresa and Sancho (2005) show the consequences of an “ecotax” and a more limited “petrol tax”. The former is closer to the modelled tax in Paper Six, as it covers a broader use of energy inputs in production. Their results show that a 10% increase in ecotax with no reduction in labour taxes produce a fall in emissions (the first dividend) however unemployment increases. Recycling the revenues through lowering labour taxes however results in both a reduction in total emissions (2.82% lower) and a decrease in the unemployment rate of 0.63 percentage points.

The authors suggest that the greater the flexibility of the labour market to produce larger changes in real wages for given changes in the unemployment rate (i.e. increasing the β parameter) the more likely it will be that a second (economic, and specifically employment) dividend will be found. To test this, in sensitivity analysis they demonstrate that with a value of $\beta = \infty$, they find a much larger fall in the unemployment rate.

8.4.3 Credibility matters for meeting policy targets

As described in Section 3.2.5, the Scottish Government has set ambitious carbon reduction targets, including reducing CO2 emissions by 42% by 2020, based on 1990 levels. This comes at a time when there is considerable discussion over the range of economic (including fiscal) levers which are under the control of the the Scottish Government. Such powers are being devolved under the Scotland Act 2012, including the powers to set marginal income tax rates for taxpayers in Scotland. Additional powers for Scotland are part of the Smith Commission recommendations (Smith Commission, 2014), promising further significant economic levers to Scotland and are, as of time of writing, beginning the progress – through which they will likely be refined – through the UK Parliament.

Whatever scope to vary (whichever) tax rates are, in future, devolved to Scotland, our results suggest that an appropriately designed ETR could bring about an improvement in the environment as well as an economic dividend. This result is true in both the short- and long-run periods. The question a policy maker would sensibly ask therefore would be whether this outcome could arise within a sufficient horizon to satisfy targeted emissions reductions (say, a reduction of 42% by 2020). Paper Six demonstrates how long it takes for the ETR to produce the desired (targeted) reduction in emissions. The length of time is counted in terms of periods, which – as in Papers Three and Four – are interpreted as years since annual data and parameters are used in the adjustments within the model.

The first thing to note is that the fall in emissions below the target of a 37% reduction on 1990 levels[51] occurs over different periods of time, depending on the form of recycling (and in each the long-run reduction in emissions is greater than 37%). When these are externally recycled (and so not returned to the economy), the desired reduction in emissions is observed before the end of the fifth period of the simulation. Recall that this is the scenario which has the most negative economic outcome, and so it is perhaps unsurprising that the emisssions reduction would occur as quickly. The fall in emissions is similarly quick in the scenario in which government revenues are recycled through increasing current spending. The slowest adjustment is seen in the case where revenues are recycled through reductions in the average rate of income tax. The model suggests that the desired reduction in emissions is reached after ten years. Each of these simulations is shown with the model specification in which agents have forward-looking behaviours. We can also interpret this as a case where industries and households have confidence that the carbon tax will persist, and are able to adjust their behaviours

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[51] Recall that this is equivalent to a 42% reduction in CO2 emissions from 1990 levels.

accordingly.

We might, by contrast, interpret the myopic specification of the model – in which agents have adaptive expectations (which constantly update, i.e. based on current values) – as being representative of conditions where there is a lack of certainty or credibility that the carbon tax will remain into the long-run. Under a lack of certainty, firms may not adjust optimally in the face of a carbon tax, and would certainly adjust more slowly. When the same scenario (a £50 per tonne CO2 tax recycled through lowering the average rate of income tax) is run with myopic behaviour, we find that it takes 25 years for the targeted reduction to be reached (i.e. 15 years more than under the forward-looking specification).

The implications for policymakers are clear. Carbon targets can be reached more quickly when the ETR commitment is credible – to both the level of the tax and the form of recycling. The notion of credibility neatly connects to a large literature on time inconsistency in carbon policy (see, for example, McGregor et al. (2012)). Time inconsistency refers to the notion that, without constructing an appropriate form of institutional change to decision-making, future policy makers will have an incentive to renege on earlier commitments. The expectation that policy will change in the future reduces the incentive for firms and households to undertake the sort of investments that the commitments are designed to encourage.

McGregor et al. (2012, p.467) describe the process through which time inconsistency in energy policy arises[52]. First, the government sets the carbon policy goal. Second, firms and households respond by making investments in technologies consistent with the stated policy, where these investments are sunk. Third, after the investments are made, governments face an incentive to “backtrack on its carbon policy *ex post* for its own political benefits”, which might include making the policy less stringent than that

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[52] McGregor et al. (2012) also discusses the “classic” time inconsistency problem of monetary policy, and similarities and differences between the framework of energy policy in the UK (including the role of the Committee of Climate Change) and the conduct of monetary policy, managed in the UK through the Bank of England’s Monetary Policy Committee.

first announced. To the extent that investors "incorporate" a belief that policy may renege on their commitments in the third step, the level of investments by households and firms may be lower than it otherwise would be.

A number of solutions to the time inconsistency problem in energy policy have been proposed, e.g. Helm et al. (2003); Brunner et al. (2012). Helm et al. (2003) argues that institutional change, such as the creation of an independent energy agency can deliver credibility through establishing a reputation for honouring commitments, and shows how welfare is improved when the government has credibility, and not the discretion to change policy.

9 Areas for future research

9.1 New technologies

Understanding the economic and environmental consequences of new industries and new energy technologies is likely to remain a common use of multi-sectoral economic models. As policymakers seek to development policy to encourage new technologies, these models – as we have seen – can provide useful *ex ante* quantification of the direction and scale of economic, energy and environmental impacts that might arise. We have discussed the applications of such approaches to onshore wind (Paper One), biofuels (Paper Two) and marine energy technologies (Papers Three and Four).

For instance, there has been a growing literature on the consequences for regional economies of the development of shale gas projects (e.g. Kinnaman (2011); Court et al. (2013)). These technologies have a distinct geographic focus – drawing from the location of shale "plays" – and draw factors of production into a regional economy, changing the nature of production and consumption in a regional economy through the purchases of goods and services locally. Court et al. (2013) notes that regional science "tools", such as those used for impact analysis including IO, SAM and CGE, "can and should" play an important role in the research on shale gas. There are also possibilities to apply these models to cases of "fracking" in the UK, as well as recent developments in support for new nuclear build, Carbon Capture and Storage and Offshore wind developments, bearing in mind the economic appropriateness of these models in each case[53].

As well as the routes between development of energy technologies and economic impacts described earlier – and the focus of the first four Papers – there is a further mechanism linking capital expenditure in particular sectors to economic impact. As briefly raised in Section 6.4.7 as the notion of "innovation", there may be spillovers between capital

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[53] Kinnaman (2011) for example, notes that early impact assessments of "fracking" in US states may overstate the economic case from inappropriate and incorrect assumptions about the nature of the regional economy, the earning of royalty incomes and the re-spending of these incomes in the local or regional economy.

expenditure in particular sectors and the level of activity in that sector (and/or related sectors). Considering only the impact of demand-side disturbances on the demand for sectoral output omits any such “competitiveness” impacts which may arise from technological learning in that sector. A separate issue is the notion of innovation within an energy technology itself – for instance, the observed reductions in unit prices of electricity supply technologies related to technology learning (Jamasb, 2007).

9.2 Local ownership, local energy and economic consequences

Paper One demonstrates the added value of a SAM analysis (relative to IO) of the assessment of an onshore windfarm with significant local community ownership. It demonstrates that the retention and use of the revenues from a community having an ownership share could be transformative for a regional economy, particularly compared with more traditional “community benefit”-style financial links between the windfarm and the local economy. Since publication, there has been continuing interest in the local and regional impacts of renewable energy and other energy projects. The lessons from Paper One could certainly make useful suggestions about the extent to which the economic impact of new sectors in a regional economy are affected by the consideration of non-wage incomes.

Furthermore, there is increasing interest by governments in the role that local energy provision – which could also involve local or community ownership in energy technologies – may play in achieving the transformation to a low carbon economy. A number of important research questions remain unanswered however. Slee (2015) has proposed a series of research needs that should accompany increased policy focus on community equity involvement in renewable energy projects. He argues this should include, (Slee, 2015, p.547) “further studies particularly in relation to the relative benefits of the different ownership models and the potential for beneficial impacts on remoter and island communities, where scope for mitigation of adverse effects of remoteness might be greater". This would be a natural step from the two extremes of ownership models considered in Paper One – a full (co)ownership share for the community compared to purely "community benefit"-style financial links between the facility and the local economy. A range of business models might include a more fuller range of funding possibilities, which ought to take into account the geographic dispersal of returns to ownership.

This point naturally leads on to a consideration of the impacts of such changes at different spatial scales, such as, for instance "local energy" proposals which have gained policy support in Scotland recently (for example, Local Energy Scotland (2015)). Such projects appear to offer opportunities for spatially defined areas to change the existing models of energy production and consumption, principally through major investment projects targeted at capital-intensive projects, such as renewable energy technologies connected at distribution level or through district heating systems.

Changes to the pattern of energy production and consumption could lead to economic and environmental changes not only in the "local" spatial scale, but also in the rest of the regional economy. Perhaps through meeting local energy needs through local generation, there would be less requirement for energy to be provided from alternative and non-local sources, which might include energy previously obtained from a gas or electricity grid. Were local electricity production to displace grid delivered energy it would be reasonable to explore the impact on emissions in both the local area – which could rise – and the larger geographic area – where emissions could plausibly reduce. This would suggest that the impact of "localising" energy production would be natural to consider within an inter-regional IO system (e.g. Allan et al. (2015b) for some initial analysis of these issues).

As identified in Section 4.4.2, there is little evidence to date on the ways in which incomes accruing to community groups are spent. Paper One made the defendable assumption that additional ownership incomes were spent in the same proportions as existing local government spending (as given in the IO table for the base year). However, the use of such incomes locally may differ. First, some areas may wish to save this "windfall" for future consumption. Second, it is common for such incomes to be considered purely as having impacts from the demand-side (e.g. Allan et al. (2011) or Okkonen and Lehtonen (2016)). This perspective then leads perhaps narrowly to the conclusion that what matters for the local economic impact of incomes is purely the combination of local content and the strength of local supply chains (as may be quantified in the multiplier effect of the expenditure itself).

Were such incomes used in alternative ways, which had their impact on the supply-side, further analysis would be more required. Examples of uses of retained incomes which would be expected to have a supply-side impact would include, for example, spending on education and training (e.g. Munday et al. (2011)), to improve the quality of the local environment, improve transport links, improve other amenities or stimulate education and training. The quantification of the alternative impacts of these different uses of incomes from both supply and demand perspectives deserves more consideration, and is perhaps an area where a CGE approach would be more suited. The work of Phimister and Roberts (2012), discussed earlier, is one example of such a use of a CGE model in this area and points a useful direction for future work. While these examples are typically from UK or Scottish contexts, the methodological applications used would have relevance for applications in other economies.

9.3 Timing and impacts from temporary demand disturbances

Papers Three and Four demonstrate the presence of "legacy" effects from a set of temporary expenditures, and this could have further applicability outside of the energy applications which were the focus of Papers Three and Four. Specifically – and an example of an area with real potential for such analysis – is in the area of tourism, particularly the literature on the *ex ante* economic impacts of hosting major events (sporting or cultural).

There are increasing applications of CGE models to tourism, for example (e.g. Li et al. (2013); Blake (2009)). One of the most widely studied tourism phenomenon are “mega events”, which are large scale sporting events such as the (football) World Cup or Olympic Games or Commonwealth Games. In the last decade it has been acknowledged in key papers in this area (e.g. Dwyer et al. (2004)) that IO modelling – previously widely used to quantify the impact of expenditures related to tourism activities – has important limitations when modelling tourism and events, and that a CGE approach may be superior.

For example, a CGE analysis is firstly able to take account of observed changes in prices caused by the existence of supply constraints, e.g. a fixed stock of accomodation. Second, a CGE model can more appropriately incorporate dynamics to the analysis. This second point could be critical if public support for events is justified on the basis of expected longer-term economic impacts, and as many tourism events are known about, with certainty, in advance. There is increasing concern, and growing evidence, that the anticipated economic consequences of hosting such mega events are unambiguously positive, which is having significant impacts on the nature and number of countries bidding to host such mega events (Zimbalist, 2015).

Recently, the candidate has undertaken analysis of the importance of model specification for the economic impacts which could arise from one-off temporary tourism expenditure (Allan et al., 2014c). The host cities for the Olympic Games, for example, are typically awarded around seven years in advance of the year in which they host the games. The economic impact of tourism linked to such a mega-event in that year – i.e. which is anticipated – is likely to be quite different to the economic impact of unforecasted tourism expenditures (for the reasons described in Section 6.4.1). Allan et al. (2014c) is primarily concerned with the tourism expenditures during the Glasgow 2014 Commonwealth Games, which, in common with the Olympics, were awarded to

Glasgow seven years prior to the date of hosting.

Allan et al. (2014c) reveals that the assumed behavioural response of firms and households, as well as the degree of pre-announcement has important consequences for the economic impact of a (one-off) temporary tourism expenditure shock. While a standard (Type I) IO analysis gives a multiplier of 1.38 for the consequence on output of a £100 million shock to tourist demand, each of the CGE specifications in Allan et al. (2014c) have a multiplier which is less than unity. There is crowding out generated in response to the tourism shock, and capacity constraints which exist in the CGE specifications which reduce the impact of a temporary demand disturbance relative to an IO analysis of the same disturbance. Curiously, the economic impact of the same disturbance is greatest in a CGE model with a backward-looking specification to firms' investment functions – typical of many CGE models with dynamics – despite this type of behaviour being unrealistic for a tourism sector experiencing a temporary increase in demand, anticipated years in advance.

Interestingly, with a forward-looking specification to the model for the behaviour of firms and households, respectively, these can undertake investment in advance of the period of the (positive) demand shock, and move consumption away from more expensive periods, and so pre-announcement appears to minimise the negative consequences of a given demand disturbance. Allan et al. (2014c) calculates that the optimal amount of pre-announcement, i.e. that which maximises the present value of the GDP impact from such an event is nine years. Indeed, the finding that a more positive economic impact occurs under the case where firms and households have advanced warning of the demand disturbance are at odds with what appears to be the only paper specifically addressing the issue of forward-looking behaviours and the impact of tourism disturbances in a CGE framework (Blake (2009)).

A second paper by the candidate explores the economic impacts of all expenditures related to the Glasgow 2014 Commonwealth Games (Allan et al., 2015a). Understanding the possible economic consequences of events, and the timing of these is important, particularly given the policy interest in using events to produce economic opportunities. From a demand-side perspective, in addition to the potential tourism disturbance *in the year of hosting*, there will be other expenditures before (as well as perhaps after) such events, including spending on infrastructure and facilities (e.g. roads, athletes housing, and sporting venues) as well as pre-event and post-event consequences for tourism. Fourie and Santana-Gallego (2011), for example, finds increases in tourism prior to the hosting of a mega event. The tourism spending related to the event must also clearly take account of the extent to which hosting events attracts new money into the region or nation or merely switches such expenditure between time periods, changes the pattern of spending (but not the level) or changes the nature of the tourist who visits the host area in the period of the events (see, for example, Preuss (2004), while the economic impact of expenditure switching was also discussed in Allan et al. (2007a)).

9.4 Energy efficiency and the economy

Paper Five showed that a CGE model is a powerful tool for considering the system-wide impacts of an improvement in energy efficiency, and to examine the scale of economy-wide rebound effects. While there has been much discussion in the literature about the scale of economy-wide rebound, and the structural and behavioural parameters which govern the scale of the effect, cited earlier, a recent paper (Gillingham et al., 2013, p.475-476) argues that the rebound debate is not important for policymakers, and that this is a “distraction” from broader support for energy efficiency measures:

> The rebound effect is real and should be considered in strategic energy planning. But it has become a distraction. A vast academic literature shows that rebounds are too small to derail energy–efficiency policies. Studies and simulations indicate that behavioural responses shave 5–30% off intended

> energy savings, reaching no more than 60% when combined with macroeconomic effects. There is ample scientific evidence to diminish undue concern about rebounds and bolster support for energy-efficiency measures.

It would seem that sensible future work on the impact of improvements of energy efficiency should continue, however the above quote suggests some natural extensions. Considering the spatial scale of the economy, CGE models can inform about the impact on economic, energy and environmental measures for that locality – be it a region or nation. The evidence seen in Section 7.5 shows that the scale of rebound varies with the economic and the energy production and consumption characteristics of the economy in question.

For some economies, the rebound effect may be less of an issue, however for others (such as Scotland) with a high degree of openness, energy intensive products and existing trade in energy, the rebound effect could have major economic as well as energy impacts. This result, while not necessarily inconsistent with Gillingham et al. (2013)'s generalisation, highlights the significances of exceptions. Rebound following an improvement in energy efficiency is an empirical issue, which has to be measured on a case-by-case basis. Part of the appropriate and continued use of CGE economic models should be to understand how the characteristics of an economy affect the potential sign and scale of rebound from energy efficiency policies. In many ways, the above quote could serve to encourage further modelling into more detailed energy-efficiency policies, for households or for (specific) industries[54], and so more closely modelling the specific actions, and consequences, of energy efficiency policy in this area.

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[54] We saw in Section 7.1 that recently there was an assessment of the consequences of distinct investments in energy efficiency in major industrial energy-intensive sectors in the UK, for instance (Parsons Brinckerhoff and DNV GL, 2015).

9.5 The labour market and the double dividend

Paper Six described a new carbon tax for Scotland, with the revenue from this recycled back to the economy to ensure that the environmental tax reform is revenue-neutral. We saw earlier how alternative treatments of the route through which the revenues are returned to the economy is critical for the scale and existence of a double dividend – where there is a simultaneous fall in emissions and an increase in measures of economic activity, including employment and GDP.

Future extensions of this paper – which are proposed in the paper itself – include replacing the assumption of public spending having a purely demand-side impact. The model could be extended to consider either the case where the revenues were recycled through expenditures on public funding for infrastructure – and so directly increasing or improving the productivity of the capital stock, which would catalyse a further supply-side consequence of the spending – or where current spending had a relationship to the productivity of other factors of production, such as labour. This latter approach could be justified on the basis that a significant portion of the Government spending in Scotland is in areas which could impact directly upon the productivity of the labour force, e.g. through funding education/training or health.

While Paper Six undertook some sensitivity analysis – particularly around the specification of agents' behaviours and parameter values – further sensitivity analysis is important to explore the strength of the papers finding of a double dividend. Specifically, it would be useful to examine more systematically the alternative specifications of the labour market, including the parameters of the wage bargaining function. The considerable literature in the area has shown that some of the early assumptions assumed "market clearing" in the labour market. These papers showed an environmental dividend but not the second (economic) dividend. It has been argued that the assumption of the labour market is critical for the appearance of a double dividend (e.g. Bovenberg and Van Der Ploeg (1998); Bosquet (2000)). Exploring the consequences of changing labour market specification and parameterisation would allow the key conclusions of the paper – that an ETR in Scotland could simultaneously meet environmental targets while improving economic outcomes – to be understood more comprehensively.

9.6 Further considerations

There are two further related points which are general to the papers included in this thesis. First, Papers Three to Six use CGE models for Scotland and the UK to explore the economic consequences of energy technologies and policies. In the description of the set up of each model, and its specific use in each of these papers, we have set out clearly the adjustments necessary to be made when modelling these different spatial levels, e.g. the degree of openness is far greater for a region (Scotland) than a nation (UK). A further example would be that labour constraints are reduced in a regional setting given the higher degree of inter-regional, rather than inter-national, labour mobility. Indeed, a common theme across all papers has been an emphasis on the necessary assumptions of the modelling approach being appropriate for the particular spatial scale to which the CGE model relates.

Second, we have been concerned throughout this thesis with the usefulness of *ex ante* economic assessments of the introduction of energy technologies and policies. Such have demonstratable benefits to policymakers seeking to understand the possible impacts of energy policy decisions. Although clearly useful, there would also be a strong argument for the complementary *ex post* study of the outturns from such decisions, e.g. the actual impacts on local/regional economic indicators of new renewable energy capacity. This could provide a way of both either "sense-checking" the results from *ex ante* treatments. If there were similarities between the results from both approaches this could secure the robustness of *ex ante* estimates, while if there were significant differences this could suggest that there was learning to be done for future *ex ante* estimates.

Some recent *ex post* analysis of the local economic impact of onshore wind farms in US counties found “an average aggregate increase in net county-level employment of 0.5 jobs per megawatt”. The authors argued that although their results were not strictly comparable to IO estimates, “our results are of a similar general magnitude to input–output derived estimated impacts” (Brown et al., 2012, p.1753). Related conceptually, there is also a growing number of *ex post* assessments of the local impacts of US shale gas extraction, also in the US (Munasib and Rickman, 2015; Paredes et al., 2015). Although there are considerable differences between onshore wind and shale energy technologies, these recent studies suggest a useful direction for guiding the robustness of *ex ante* economic impacts of new energy technologies.

10 Conclusions

This thesis has sought to argue that carefully implemented multi-sectoral economic modelling approaches – specifically Input-Output, Social Accounting Matrix and Computable General Equilibrium analyses – can be used to generate policy-relevant insights into the consequences of energy technologies and policies on energy, economic and environmental measures. In this thesis we have described the contributions made by a total of six papers which have used these models to consider the impacts of – in turn – a new onshore windfarm, biofuels production, developments in marine energy capacity, energy efficiency policies and an environmental tax reform (specifically a revenue-neutral hypothetical carbon tax).

All papers considered in this thesis were published in peer-reviewed academic journals between 2007 and 2015. These papers were selected as they provide a range of applications of such techniques and demonstrate how these can be appropriately used to quantify impacts, while additionally these are the areas of continued policy focus not only in the UK and Scotland (to where the focus of the empirical papers in this thesis relate) but across the world. The contribution of each paper is organised by Chapters, which are sequenced to demonstrate a progression from IO and SAM analysis to more flexible (and complex) CGE modelling techniques.

We have seen that such models can assist the identification of the impacts of developments in energy technologies or changes in energy policies, and shed useful light on the extent to which there may be trade-offs between the multiple objectives of energy policy. By isolating the transmission mechanisms between the policy instrument and the economic outcomes that this produces, such models serve a useful function in both quantifying the scale of possible changes, and also identifying potential unintended consequences of such policies. Used sensibly therefore, such models can allow for the better design of actual or hypothetical energy policies. As well as noting the contribution of each paper to the academic and policy literature. Chapter 9 outlined a number of ways in which the works developed through the papers in this thesis can be developed to consider further aspects of the consequences of energy policies and technologies.

Aside from alternative empirical applications, future work may extend some of the methodologies used in the papers in this thesis in a number of different directions. First, all the empirical analysis in these papers used a single-regional scale (although Paper Two does discuss papers which have inter-regional specifications). Many of the issues here could naturally be extended to the inter-regional framework – as discussed in Section 9.2, for instance. Additionally, where there is likely to be increasing economic levers devolved to Scotland within the UK, the case for considering the consequences of policy divergence in an inter-regional framework becomes strong. This chimes with both increasing devolution and decentralisation issues in economic, as well as energy, policy. With a consideration of the notion of inter-regional models, there is a massive literature on the so-called "New Economic Geography" literature and some recent work bringing the insights from this into multi-regional CGE modelling (e.g. Santos et al. (2013) and Haddad and Hewings (2005)).

Second, there would appear to be potentially interesting opportunities to extend the treatment of agents behaviours in CGE models beyond those used in the Papers Three to Six, which considered myopic and perfect foresight variants for households and firms. From this, we saw results which were both in line with expectations about the timing of impacts from temporary demand disturbance, and useful for policymakers. Other specifications of behaviour are becoming studied in the CGE modelling literature, including models with habit formation (e.g. Lecca et al. (2011)) and models with hyperbolic discounting, e.g. time-varying discounting of consumption. These appear to be very useful avenues for future developments of the models included in this thesis. Lecca et al. (2011), for instance, show how the presence of internal habit persistence over consumption affects the (short-run) impact household improvements in energy efficiency[55]

Third, CGE models have at their core a complete characterisation and coverage of the whole economy, which can shed light on market interactions. Where there might be exciting opportunities to further develop CGE models is through the combination with other models which have a different (e.g. partial) focus. One such avenue would be integration between energy systems models and CGE frameworks, which have been described as "bottom-up" and "top-down" models respectively (e.g. Böhringer (1998)). The case for combining CGE models with energy system models hinges on the use (in CGE) of aggregate production functions, and the necessary assumptions about substitution parameters in such a framework. It has been argued that "the usual CGE representation of energy conversion by means of restrictive CES functions causes doubts among many energy systems analysts about the credibility of CGE-based energy policy simulations" ((Böhringer, 1998, p.234)). Energy systems models – with a partial but realistic assessment of energy technology options – provide a powerful tool for analysis.

As has been noted however, differences between top-down (i.e. CGE) and bottom-up (i.e. energy systems models) are important, but modellers should not attempt to seek the superiority of one over the other: "it is often overlooked that these differences [between top-down and bottom-up approaches] are less of a theoretical nature but simply relate to the level of aggregation and the scope of *ceteris paribus* assumptions. As pointed out in previous methodological papers general economic theory provides a unifying concept for both approaches" (Böhringer (1998, p.235)). Recent work (e.g. Böhringer and Rutherford (2008, 2009)) has examined how the technological detail in energy models can be combined with the whole economy coverage and internal

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[55] In Lecca et al. (2011), internal habit formation relates households consumption to their past consumption, and differs from "external habit", in which households habit are affected by consumption at the level of the economy as a whole. They find that "the introduction of habit changes the composition of household consumption only in the short-run and in the transitional path towards the long-run equilibrium" (Lecca et al., 2011, p.8).

consistency of CGE models to offer a strong direction for future work in the use of multi-sectoral economic modelling approaches to specific policy-relevant questions in the energy sphere.

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A Calculation of the conventional multiplier in fixed-price analysis

IO linkages and Type I multipliers

The conventional IO approach begins with the economic system as a set of equations relating output X for sector i as the sum of sales to, in turn, itself (X_{ii}), to sector j (X_{ij}) and to final demand F_i:

$$X_i = X_{ii} + X_{ij} + F_i \tag{13}$$

With N sectors, the output of all sectors can similarly be specified:

$$\begin{aligned} X_1 &= X_{11} + X_{12} + \ldots + X_{1N} + F_1 \\ X_2 &= X_{21} + X_{22} + \ldots + X_{in} + F_2 \\ &\vdots \\ X_N &= X_{N1} + X_{N2} + \ldots + X_{NN} + F_N \end{aligned} \tag{14}$$

Matrix T_{11} in Table 1 gives the expenditure flows between sectors, X_{ij}, which is used to construct a square matrix of “technical production coefficients” with elements a_{ij}. These are necessary to characterise, for the initial set of IO tables, the production structure of each sector. Individual elements in the resulting A matrix, a_{ij}, where X_j gives total inputs to sector j,are calculated as:

$$a_{ij} = X_{ij}/X_j \tag{15}$$

So that the A matrix has the properties:

$$A = \begin{pmatrix} X_{11}/X_1 & X_{12}/X_2 & \cdots & X_{1N}/X_N \\ X_{21}/X_1 & X_{22}/X_2 & \cdots & X_{2N}/X_N \\ \vdots & \vdots & \ddots & \cdots \\ X_{N2}/X_1 & X_{N2}/X_2 & \cdots & X_{NN}/X_N \end{pmatrix} \tag{16}$$

We can then restate equation 16 above in terms of our new A matrix:

$$\begin{gathered} X_1 = a_{11}X_1 + a_{12}X_2 + \ldots + a_{1N}X_N + F_1 \\ X_2 = a_{21}X_1 + a_{22}X_2 + \ldots + a_{iN}X_N + F_2 \\ \vdots \\ X_N = a_{N1}X_1 + a_{N2}X_2 + \ldots + a_{NN}X_N + F_N \end{gathered} \tag{17}$$

Rearranging, we get:

$$\begin{gathered} (X_1 - a_{11}X_1) - a_{12}X_2 - \ldots - a_{1N}X_N = F_1 \\ -a_{21}X_1 - (X_2 - a_{22}X_2) - \ldots - a_{iN}X_N = F_2 \\ \vdots \\ -a_{N1}X_1 - a_{N2}X_2 - \ldots - (X_N - a_{NN}X_N) = F_N \end{gathered} \tag{18}$$

or

$$\begin{gathered} (1 - a_{11})X_1 - a_{12}X_2 - \ldots - a_{1N}X_N = F_1 \\ -a_{21}X_1 - (1 - a_{22})X_2 - \ldots - a_{iN}X_N = F_2 \\ \vdots \\ -a_{N1}X_1 - a_{N2}X_2 - \ldots - (1 - a_{NN})X_N = F_N \end{gathered} \tag{19}$$

In matrix form, we can represent Equation 19 as:

$$(I - A)X = F \tag{20}$$

where I is an N x N identity matrix with ones on the diagonals and zero elsewhere:

$$I = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \cdots \\ 0 & 0 & \cdots & 1 \end{pmatrix} \tag{21}$$

Restating in terms of gross output (X), we can see that output is found by the multiplication of matrix by the level of final demand and the interconnections as given by the Leontief inverse:

$$X = LF \tag{22}$$

where $L = (I - A)^{-1}$.

Conventional demand-driven IO modelling traces the consequence for aggregate economic activity (X) of changes in a vector of final demand for sectoral output (F) given the Leontief inverse matrix (L) (Miller and Blair, 2009). The marginal impact on aggregate – i.e. whole economy – output (X) of marginal changes in exogenous final demand F will therefore be:

$$\Delta X = L\Delta F \tag{23}$$

where individual elements of the L matrix show for a change in demand for the output of sector j, the consequence for sector i output, e.g.:

$$\partial X_i/\partial F_j = l_{ij} \tag{24}$$

For unit changes in demand for the output of sector j therefore, the aggregate effect on output will be given by the sum of the elements in the j-th column of the L matrix:

$$o_j = \sum_{i=1}^{N}(l_{ij}) \tag{25}$$

where o_j is the output multiplier for sector j.

The output multiplier can be explained as follows: an increase in exogenous demand for the output of sector j (the direct effect), in turn increases demand for those sectors to whom the directly stimulated sector is linked through intermediate purchases (as given in the j-th column of A matrix). Additionally, those sectors to which *those* indirectly stimulated sectors are linked through their intermediate purchases are also stimulated, and so on. In this process, the economic impact from the (direct) change in the final demand for the output of a specific sector "ripples" throughout the rest of the economy producing a change across (potentially, although it will depend upon the linkages among sectors) all intermediate sectors in the economy.

The ratio of the direct effect to the total effect on output is termed the output multiplier. It is assumed that the impact of changes in final demands for the output of sectors are transmitted via the Leontief inverse in which industrial sectors are endogenous, but households are exogenous. This is the Type I closure, in which increased economic activity contributes to a "multiplier" impact only through inter-sectoral linkages. "Leakages" at each "round" of the multiplier process – such as inputs either imported or from non-endogenised sectors or factors of production – mean that the multiplier value is finite. Such leakages ensure that the sum of the j-th column in the A matrix is less than one.

The multiplier process can alternatively be thought of as occurring through a process of "rounds". The direct effect Δf, stimulates demand for the inputs to the directly stimulated sector in the first "round", $L\Delta f$, then those sectors stimulated in the first round themselves stimulate demand for inputs from other sectors in the second round, $L^2\Delta f$, and so on, through to round t:

$$\Delta X = \Delta f + L\Delta f + L^2\Delta f + L^3\Delta f + \ldots + L^t\Delta f \tag{26}$$

If the change in demand is for the output of sector j, this "decomposition" of impacts across time suggests that the change in output can also be spread across sectors. For instance, in the first round, sector j will increase its output, before – in the second round – those sectors to which sector j is connected through the Leontief inverse will increase their output. The third round will see indirectly stimulated sectors, and sectors linked to those indirectly stimulated, increase their output, and so on through rounds four to t. The multiplier is largely a story relating to the early rounds: (Miller and Blair, 2009, p. 33) note that, in many applications it has been found that after L^7 or L^8, the terms multiplying Δf become insignificantly different from zero". We will see in Chapter 6 how the rounds of IO multiplier has been used to distribute the multiplier impacts of changes in demand across time.

IO Type II multipliers

Above, we assumed that the impact of a change in final demands for the output of sectors are transmitted via a Leontief inverse in which only production sectors are endogenous. In that system, households (as receivers of income and consumers of goods and services) are exogenous. Where changes in F produce a change in economic activity, this would have consequences for the level of labour income, which could sensibly be expected to have an impact on the level of household consumption. The Type I approach does not consider such changes.

If additional income (assuming a positive change in Final demand) is respent in the economy there would be an additional impact on economic output and activity, with a correspondingly larger multiplier i.e. the total impact on aggregate would be larger, for the same direct change. Capturing this additional impact is referred to as “closing” the model with respect to households, or making the household sector “endogenous”, with the multipliers from the extended Leontief inverse with (now) $N+1$ sectors referred to as Type II (Miller and Blair, 2009).

Miller and Blair (2009) explain that other final demand categories can be endogenised, but that “closure with respect to households is more usual”(Miller and Blair, 2009, p. 35). This requires the addition of a new row and column to the A matrix, with row coefficients equal to:

$$a_{n+1,j} = z_{n+1,j}/x_j \tag{27}$$

where $z_{n+1,j}$ is the value of purchases of labour by the j-th sector.

The coefficients for the additional household column are found by dividing the purchases by households from sector i ($z_{i,n+1}$) by the the total output of the household sector (x_{n+1}):

$$a_{i,n+1} = z_{i,n+1}/x_{n+1} \tag{28}$$

Conventionally, the figure for total household output is equal to the measured total of household labour income from the IO tables: (Miller and Blair, 2009, p.36), for example, refer to household total output as “measured by income earned”. While missing from earliest discussions of multipliers, an early reference to an induced multiplier (Hirsch, 1959, p. 364) notes:

> “Model II makes allowance also for consumer expenditure adjustments, which come about because of output changes and which lead to a chain reaction of interindustry reactions in income, output and once more on con-

> sumer expenditures. There can be different versions of model II, depending on the assumptions about the income-consumption function. By and large, consumption expenditures tend to vary less than income. Although under such conditions the income-consumption function would tend to be curvilinear, for simplicity's sake this study assumes a linear relationship. For this reason the income multiplier of model II will tend somewhat to overstate the income effect"

The same paper also notes (Hirsch, 1959, p. 362) that the household output figures *do* comprise more than labour income, e.g. "wages and salaries including bonuses and retirement benefits, depreciation, interest, dividends, non-corporate profits, retained earnings, and various subsidy payments...Since no appropriate data... exist... household outputs were taken from company information which took the form of sector payments to households".

The Type II output multiplier will therefore be larger than the Type I due to the inclusion of additional income-expenditure links. Changes in the level of (wage) income will feed to changes in the level of expenditure by households, with the pattern of "inputs" to household consumption given by the vector T_{13} (Table 1). One assumption therefore is that the average purchasing pattern by households in the period of the IO tables can be used to represent the impact of marginal changes in household incomes.

SAM multipliers

In a SAM system, we can partition economic activity in an economy to describe the production system as follows:

$$\bar{x} = S\bar{x} + \bar{f} \tag{29}$$

where $\bar{x}$ is a vector of outputs for all accounts (endogenous and exogenous), $\bar{f}$ is a vector of final demands for all accounts and where S is a matrix of SAM technical coefficients calculated as in equation 3. The dimensions of S reflect the number of endogenous accounts considered. For a SAM with the structure of Table 2:

$$S = \begin{pmatrix} A_{11} & 0 & C_{13} \\ V_{21} & 0 & 0 \\ 0 & Y_{32} & H_{33} \end{pmatrix} \tag{30}$$

where A_{11} is the matrix of interindustry technical coefficients (and so identical to the A matrix for an IO system), C_{13} is a matrix of consumption coefficients for endogenous final demand categories and V_{21} is a matrix of value added (factor) coefficients. Y_{32} is a matrix showing inter-institutional transfers which distribute returns from income to value-added categories (i.e. the capital and labour share in factor returns) and H_{33} is the matrix denoting the shares of income transferred between endogenous final demand categories.

For a given SAM matrix S we can hence define a multiplier matrix (M) which captures not only interindustry (Type I) and associated wage-consumption interactions (Type II) but further SAM interactions, which take into account all forms (and uses) of endogenised income-consumption components. Miller and Blair (2009) note that since SAM multipliers include (and endogenise) transactions not included in the IO model, "SAM multipliers will generally be larger than the input-output multipliers and with endogenised final demand as well the multipliers will be larger still".

B Contribution to multi-authored works

Paper one

Co-authors: Kim Swales and Peter McGregor (both University of Strathclyde)

Statement of my contribution to the paper:

- Develop idea for paper through discussion with co-authors
- Obtain Social Accounting Matrix data for Shetland economy
- Construct Social Accounting Matrix for Shetland with alternative characterisation of onshore wind projects under two central scenarios
- Prepare drafts of paper for discussion, discuss and agree revisions to paper and make revisions following comments from co-authors
- Submit paper to academic journal (Journal of Rural Studies, September 2008)
- Submit paper to Regional Studies (October 2008 and November 2008)
- Lead on responding to referees comments and revising manuscript in light of comments
- Resubmit revised (final) manuscript to Regional Studies (January 2010)

Paper three

Co-authors: Michelle Gilmartin (University of Stirling)

Statement of my contribution to the paper:

- Develop idea for study to use CGE model for series of temporary demand disturbances related to marine energy development in Scotland
- Obtain expenditure series from Sgurr Energy and IPA (2009) report and construct

appropriate expenditures through adjusting for local (non-Scottish) content and matching to industrial sectors of Scottish economy

- Design model simulations and produce results for central and sensitivity simulations
- Prepare drafts of paper for discussion, discuss and agree revisions to paper and make revisions following comments from co-author
- Collaborate with co-author in responding to each referees comments through revision of paper, including edits to manuscript and creation of response to referees through two rounds of referees comments

Paper four

Co-authors: Patrizio Lecca, Peter McGregor and Kim Swales (all University of Strathclyde)

Statement of my contribution to the paper:

- Develop idea for study to use CGE model with forward-looking expectations (Lecca et al, 2013) for series of temporary demand disturbances
- Obtain expenditure series from Crown Estate report and construct appropriate expenditures through adjusting for local (non-Scottish) content and matching to industrial sectors of Scottish economy
- Perform model simulations and produce results with guidance from co-author (Lecca)
- Prepare drafts of paper for discussion, discuss and agree revisions to paper and make revisions following comments from co-authors
- Submit paper to Marine Policy (December 2012 and January 2013)

- Lead on preparing response to referees comments and revising manuscript in light of referees comments
- Resubmit revised manuscript to Marine Policy (April 2013)

Paper five

Co-authors on paper: Nick Hanley (University of Stirling), Peter McGregor (University of Strathclyde), Kim Swales (University of Strathclyde) and Karen Turner (Heriot-Watt University)

Statement of my contribution to the paper:

- Idea for paper came through work done by authors of paper for DEFRA, published in report January 2006
- Construct economic and environmental database for UK into modelling framework previously used for Scotland and other regional economies, new model termed UKENVI
- Construct UK Input-Output database for 2000 based on rolling-forward tables for earlier years
- Sectors identified included use of experimental disaggregation of electricity sector in IO accounts
- Construction Income-Expenditure accounts for the UK in same year to generate balances Social Accounting Matrix for 2000 as base-year database for CGE modelling
- Run model simulations, including extensive sensitivity analysis around key parameters
- Comment on drafts of manuscript and prepare additional results and material in light of referees comments prior to resubmission.

Paper six

Co-authors on paper: Patrizio Lecca, Peter McGregor and Kim Swales (all University of Strathclyde)

Statement of my contribution to the paper:

- Work developed as part of research programme for ClimateXChange Scottish Government funded centre of expertise on climate change, for which I was the full time representative.
- Idea for paper developed in discussion with co-authors, including discussion around Scottish climate targets.
- Developed the novel sectoral disaggregation of the electricity sector used in the CGE modelling framework
- Electricity sector in IO tables split into non-generation activities (e.g. transmission, distribution and supply) with disaggregation by generation type
- Assisted in the drafting of manuscript for academic journal (Ecological Economics)
- Commented on drafts of manuscript prepared for journal and prior to resubmission.

Signed:

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