Supporting Information

Indirect CO_2 emission implications of energy system pathways: Linking IO and TIMES models for the UK

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8-page Supporting Information

One attachment: *daly-EST-SI-20140629-xls.xlsx*

Summary of Tables:

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1 S1: Modelling context

Energy systems modelling & the UK TIMES model (UKTM)

Bottom-up ESOMs calculate the optimal set of technology choices to achieve specific targets, meeting energy service demands and a variety of resource and technical constraints, subject to assumptions regarding future resource and technology costs and availability. The optimum is calculated on the basis of least cost, or maximum utility in a partial equilibrium framework, where energy service demands reduce in response to price. One such framework, TIMES (The Integrated MARKAL-EFOM System), is a model generator for local, national or multi-regional energy systems. It was developed and is maintained by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement of the International Energy Agency (IEA). The TIMES/MARKAL family of modelling tools are being used by approximately 177 institutions in 69 countries. TIMES equations are based on a linear optimisation formulation: The full mathematical description of TIMES is described by Loulou and Labriet [1].

The partial equilibrium, technology detailed framework of ESOMs make them well-suited to investigating the economic, social, and technological trade-offs between long-term divergent energy scenarios, and for examining least-cost pathways for reaching decarbonisation targets.

The ESOM used in this study is UKTM (the UK TIMES Model), built in the TIMES framework, which portrays the UK energy system, from fuel extraction and trading, to fuel processing and transport, electricity generation and all final energy demands[2]. The model generates scenarios for the evolution of the energy system based on different assumptions around the evolution of demands, future technology costs, measuring energy system costs and all greenhouse gases (GHGs) associated with the scenario. As a partial equilibrium energy system and technologically detailed model, is developed in order to investigate the economic, social, and technological trade-offs between long-term divergent energy scenarios. UKTM is the successor and an evolution of the UK MARKAL model[3], which underpinned the analysis behind much of UK energy policy.[4]

Environmentally-extended input-output modelling & UK EE-MRIO model

Environmentally-extended multi-regional input-output (EE-MRIO) analysis is a recognised, peer reviewed method for calculating consumption-based emissions for the purpose of global sustainability analysis[5]. In 2011 the UK Department for Environment, Rural and Food Affairs, Defra, commissioned the University of Leeds to provide annual consumption-based accounts employing a UK centric EE-MRIO, to be published annually as an official environmental indicator[6]. A variant of the UK EE-MRIO has provided evidence to the Waste and Resources Action Programme (WRAP) to investigate the contribution of resource efficiency strategies to meeting climate change targets[7, 8], been integrated with a process lifecycle database to estimate the upstream impact of energy technologies[8, 9], informed UK government on widening the scope for climate mitigation policy[10] and provided evidence to Defra on the climate impact of the transition to a service-based economy.

In the EE-MRIO model, emissions directly emitted by industry sectors is reallocated through complex supply chains to the finished products in which it becomes embodied, using the standard input-output equation originating from Leontief[11] and used by many in footprint analysis[12, 13]. National consumption-based emissions are the sum of embodied carbon along these complex supply chains to meet absolute demand for finished products. Energy demand will not just induce production in the UK economy but will induce global production activities, resulting in emissions being released outside of its national territory. Emissions embodied in final products can be traced to the country and sector in which they were produced. Around 50% of emissions embodied in products consumed in the UK are produced abroad, which for some manufacturing sectors e.g. electronic machinery and equipment can be greater than 80%[14]. On average, manufacturing is more intensive abroad and the UK increasingly imports manufactured products from China, which has a higher carbon intensity of production.

2 S2: Illustration of generation of IEFs and removing double counting

Generation of IEFs

This study employs a two region global input-output model [8] updated to 2008 (the latest data year available at project commencement). A linear production function relates direct inputs used to produce 1 unit of industries' product output, which when inverted using the Leontief inverse shows the direct and indirect requirements of one unit of industries' output – the total input coefficient. By attaching a direct emission intensity to industry sectors and propagating it through the trade transactions in the MRIO model, the method generates direct and indirect emission factors (IEFs, also referred to as multipliers, coefficients and factors) measured in terms of emissions per unit of economic output (CO_2/£). These account for the full supply-chain emissions embodied in a sector's product (defined by its economic output). The following illustrates how IEFs are calculated using the IO model.

The production of electricity from coal does not only produce emissions when the coal is combusted but also in the construction and operation of a power station. Production of a power station does not end with the purchase of concrete, machinery, equipment and other components. It generates a long chain of interaction in the production processes since each of the products used as inputs need to be produced and will, in turn, require various inputs. Production activities are not constrained to the UK due to international trade. Mined, processed and manufactured materials and products will be sourced from abroad. The result is in infinite layer of supply chain processes and associated emissions, the sum of which is determined by EE-MRIOA.

The first stage calculates direct sector multipliers equal to the emissions released by sector (i.e. production-based accounts) divided by its total output. This is required for all sectors in all countries. Using a simple example, if electricity production from combustion of coal emits 20 grams of CO_2 to produce £20 of output, one production unit emits 1 gram of CO_2 i.e. its production intensity is 1 gram CO_2/ £. However, electricity provision has additional indirect emissions embodied in its intermediate inputs. Imagine 2 units (£) of concrete and 3 units (£) of machinery are required. If the concrete sector emits 10 grams of CO_2 to produce £20 of output and machinery manufacturing emits 10 grams of CO_2 to produce £50 of output, their production intensities are 0.5 grams CO_2/ £ and 0.2 grams CO_2/ £ respectively. 2 units at an intensity of 0.5 grams CO_2/ £ and 3 units at an intensity of 0.2 grams CO_2/ £ are reallocated to the electricity sector as indirect intensity multipliers. The total intensity multiplier (i.e. direct plus indirect) of the electricity sector is 2.6 grams CO_2/ £. In reality, the concrete and manufacturing sectors will have intermediate inputs and emissions will be reallocated from the point of origin through supply chains to the final product. The demand for electricity determines the total consumption-based emissions: if householders purchased £5 of electricity the associated consumption emissions would be (5 * 2.6) 13 grams CO_2. The electricity sector can source machinery domestically or import the same product from another country which may have more carbon intensive production.

Removing double counting

The IEFs generated for some MRIO sectors must be altered to remove double counting. This double counting can arise when the IEF for a sector encompasses the entire supply chain upstream of that sector, and UKTM accounts for the upstream emissions separately: The IEF applied to each technology (or stage in the energy system) should encompass only the additional emissions from that process. For example, fuel processing-related MRIO sectors include the emissions embodied in not only fuel processing, but in upstream fuel mining and transportation. As fuel mining and transport-related indirect emissions are already counted separately in UKTM they must be removed from fuel processing. The IEF is disaggregated to show the distribution of carbon across UK and rest of world sectors and those attributed to mining sectors can be excluded from the IEF. Double counting of indirect emissions is only an issue for the mining, distribution and processing stages as the corresponding MRIO sectors are all linked to producing a secondary fuel. The IEF associated with power generation in the MRIO model is only associated with power generation, and not upstream fuel supply or extraction (as stipulated in the SIC).

However, the mining and processing sectors are not directly linked in the MRIO model. There are four mining sectors for energy sources: coal, oil, gas and uranium. However, there are not four corresponding processing sectors. For processing we use several sectors including: coke oven products, motor spirit (gasoline) and industrial gases. It is straightforward to subtract emissions from direct (i.e. on-site) mining activities (see **Table 3**), which has the highest contribution besides manufacturing emissions; however, there will be some emissions upstream of mining in the processing emissions that are not distinguishable between mining and processing. Mining will for example have required machinery and energy inputs yet the IEFs don't distinguish the share of these emissions compared to energy and machinery for processing alone. However, activity further from the first layer of the supply chain the impact diminishes considerably[15]. In the example given in **Table 3**, to extract one unit (£) of oil 0.51 g CO2 are emitted domestically. To process gasoline, 0.77 g CO2 are produced, however, this includes 0.18 g CO2 from mining activities therefore there would be some double counting. Emissions from the equivalent mining sectors, in this example oil mining, are deleted from the gasoline IEF, reducing emissions from processing only to 0.59g CO2.

Table 3: Worked example of excluding double counting from gasoline IEF.

	Oil: Crude petroleum and services related to crude oil extraction, excluding surveying (kg/£)	Motor spirit (gasoline) (kg/£)	Motor spirit (gasoline) (kg/£) - exclude double counting
Agriculture and mining	0.43	0.18	0
Manufacturing	0.01	0.52	0.52
Energy and utilities	0.05	0.05	0.05
Construction	0.00	0.00	0.00
Services	0.02	0.01	0.01
Total IND-D	0.51	0.77	0.59

3 S3 – Domestic IEF emissions intensity trajectories

We use the simplification that domestic indirect emission trends are driven on aggregate by the carbon intensity of the UK industrial sector. We take this trajectory for two scenarios, *Reference* (no CO_2 target), and *2050 80% target* (UK energy system decarbonises by 80% on 1990 levels by 2050), and apply these to future domestic IEFs. **Table 4** describes the trajectories used. For 2050 in the reference scenario, domestic indirect emissions are assumed to be 40% less intensive than in 2010: This figure depends on whether the UK economy would decarbonise at this rate and results should be interpreted in this light.

Table 4: Emission trajectories (gCO_2/MJ, indexed on 2010 = 1) for the UKTM industrial sector

Scenario	2010	2020	2030	2040	2050
Reference	1	0.86	0.72	0.64	0.60
2050 80% target	1	0.84	0.56	0.37	0.37

4 S4 – CO2 constraint imposed on each scenario

Table 5 describes the CO_2 constraint for each scenario and which emissions the constraint refers to, Direct Emissions (DE), Indirect Emissions – Domestic (IED), and Indirect Emissions – Non-domestic (IEN). S3 and S4 have a higher emissions cap than S2 because UKTM in S2 has full domestic emissions coverage, and therefore adding additional domestic emissions via IED without rebalancing the emission cap would not be appropriate. We increase the cap by measuring IED in 2010 and assuming that in S2, they grow according to the average UK industrial sector emissions intensity (Supporting Information S3).

Table 5: Level of CO_2 target imposed for scenarios 2-4a, and the emissions the target constraints (Direct Emissions (DE), Indirect Emissions – Domestic (IED), and Indirect Emissions – Non-domestic (IEN))

Scenario	Emissions constrained	Level of target (MtCO2)						
		2020	2025	2030	2035	2040	2045	2050
S2	DE	442	388	336	283	230	177	124
S3	DE, IED	442	340	337	285	233	180	128
S4	DE, IED, IEN	442	340	337	285	233	180	128
S4a	DE	386	328	288	231	176	121	56

5 S5 - Indirect emissions of different technologies and energy vectors

The values of indirect emissions produce a wide range of values for different energy vectors, depending on the source of primary fuel (imported or domestically mined, and at which cost step) and method of production (electricity, hydrogen, biofuel or oil produce generation). The supporting information describes the indirect emission factor for each technology in UKTM and its derivation, and **Figure 2** summarises the range from each category of primary fuel source and secondary generation, giving the maximum and minimum IEF value for each category between 2010 and 2050. In general, non-domestic IEFs are higher for most technologies. In particular, non-domestic IEFs are high for imports, particularly for electricity and biofuels.

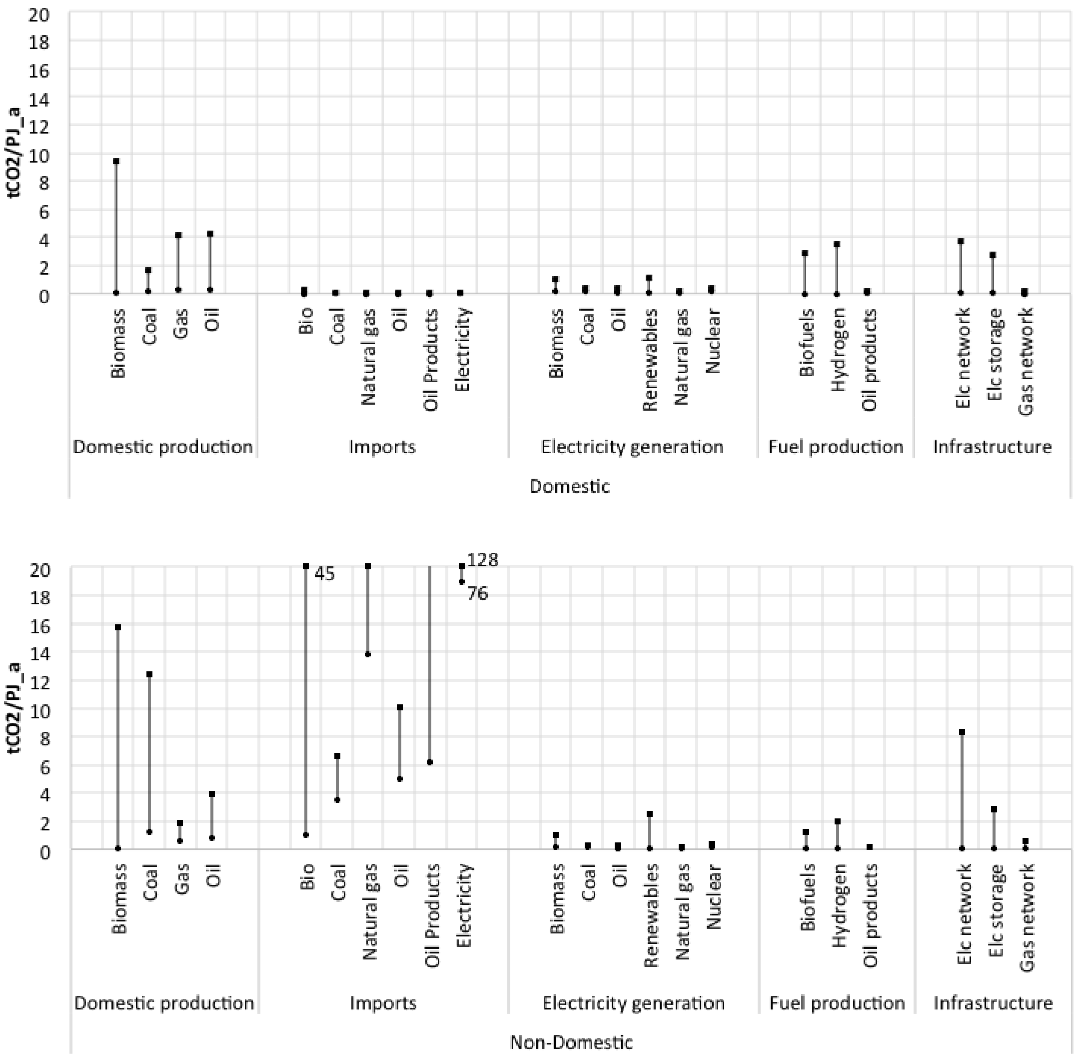

Figure 2: Ranges of indirect emissions values for domestic and non-domestic for different energy vectors per unit of capacity (PJ_a), adjusted to remove double counting. Domestic production refers to UK extracting and mining activities for fossil resources, and biomass production.

6 S6 – Calculated IEFs for UKTM technologies

Attached spreadsheet

7 S7 – Detailed allocation of UKTM technologies to SIC classifications

Attached spreadsheet

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